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The recovery of cod in the Baltic Sea, a success against all odds

Friedrich W. Köster, Margit Eero and Bastian Huwer

$$M2_i = \frac{\sum_j \frac{dR}{dt} N_j \frac{\varphi_{ji}}{\varphi_i}}{N_i \omega_i} \int_a^b \varepsilon \Theta^{\sqrt{17}} + \Omega \int \delta e^{i\pi} = \{2.7182818284\}$$

∞ χ^2 \sum $!$ $>$ ω

Content of the talk

1. Population dynamics and stock status of eastern and western Baltic cod
2. Reasons for recovery of the eastern cod: management or biology?
3. Processes affecting recruitment, state of knowledge so far
4. What has changed?
5. Things to come

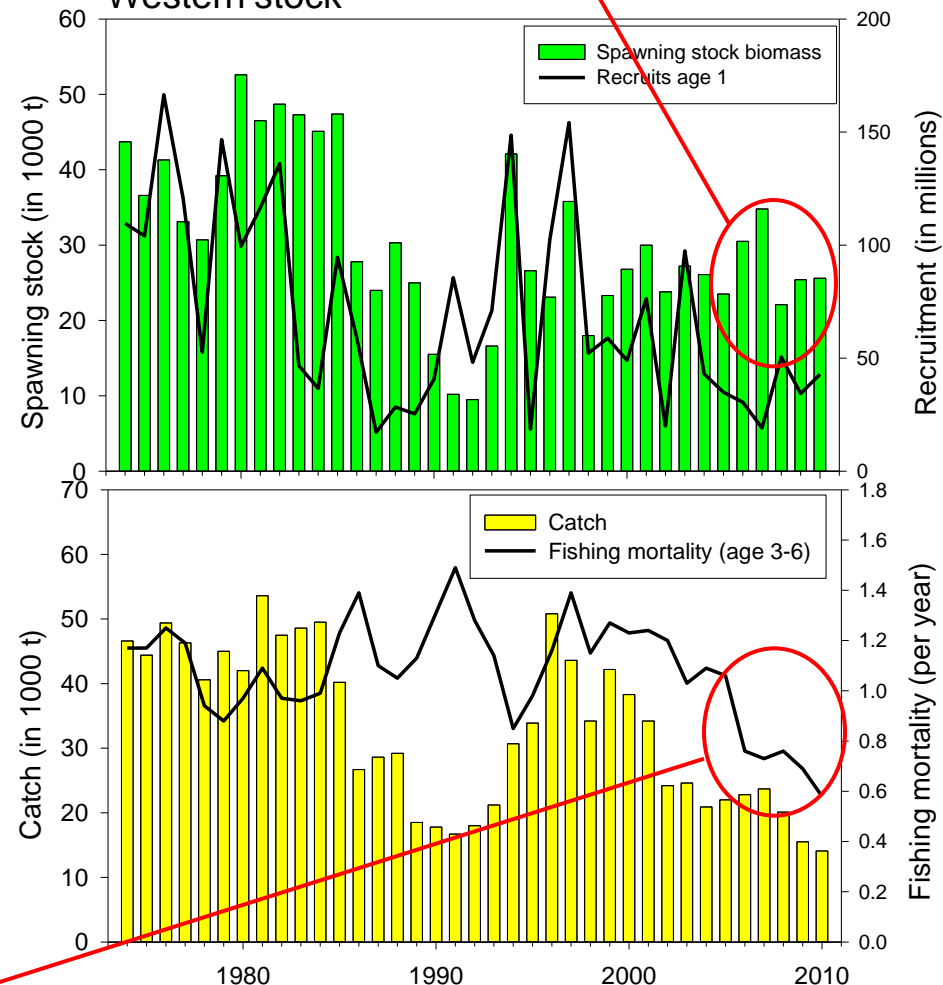
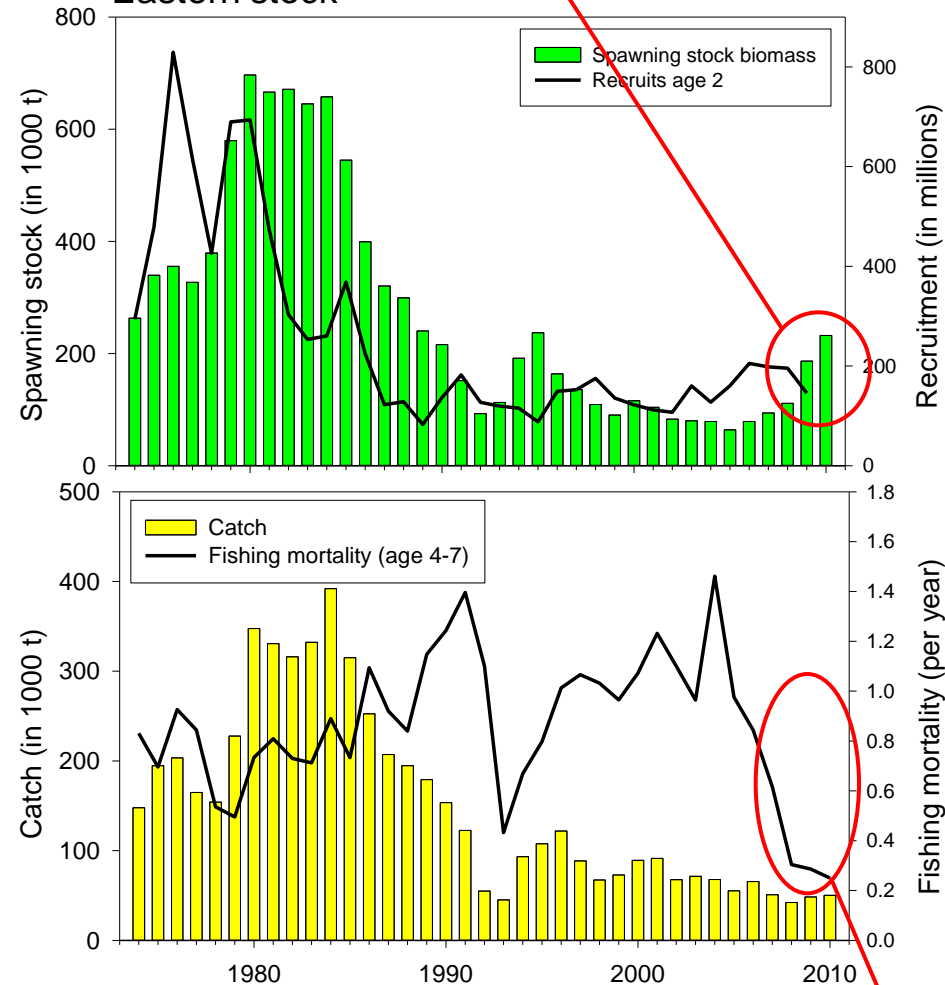
Baltic cod stock dynamics

Increase in spawning stock,
expected value in 2011: 310.000 t

No increase in spawning stock

Eastern stock

Western stock



Fishing mortality declined

Stock status

Eastern stock

F (Fishing Mortality)			
	2008	2009	2010
MSY (F_{MSY})	✓	✓	✓
Precautionary approach (F_{pa}, F_{lim})	✓	✓	✓
Management plan (F_{MGT})	✓	✓	✓
SSB (Spawning Stock Biomass)			
	2009	2010	2011
MSY ($B_{trigger}$)	?	?	?
Precautionary approach (B_{pa}, B_{lim})	?	?	?
Qualitative evaluation	→	↗	✓

Appropriate status according to all fishing mortality (F) limits and targets

Stock biomass limits not defined, but above all candidates

Western stock

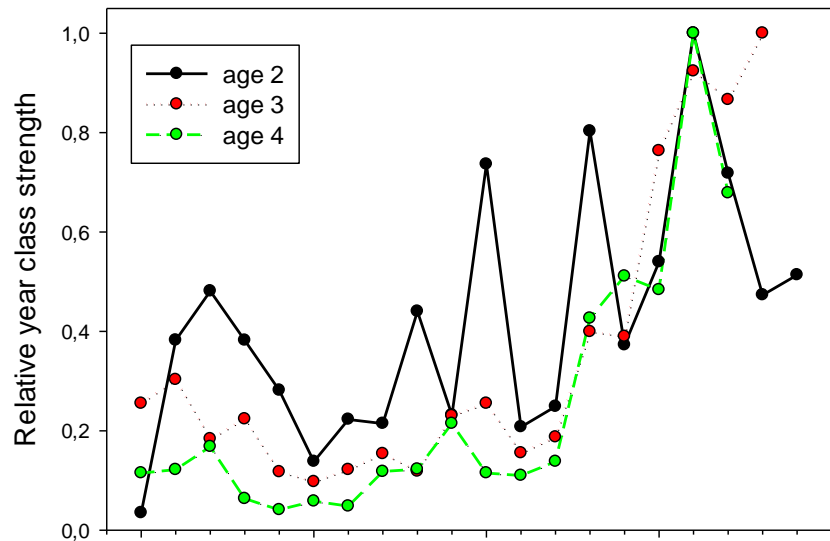
F (Fishing Mortality)			
	2008	2009	2010
MSY (F_{MSY})	✗	✗	✗
Precautionary approach (F_{pa}, F_{lim})	?	?	?
Management plan (F_{MGT})	✗	✗	✓
SSB (Spawning Stock Biomass)			
	2009	2010	2011
MSY ($B_{trigger}$)	✓	✓	✓
Precautionary approach (B_{pa}, B_{lim})	✓	✓	✓
Management plan (SSB_{MGT})	?	?	?

Huge difference between target F in management plan (0.6) and F at MSY (0.25)

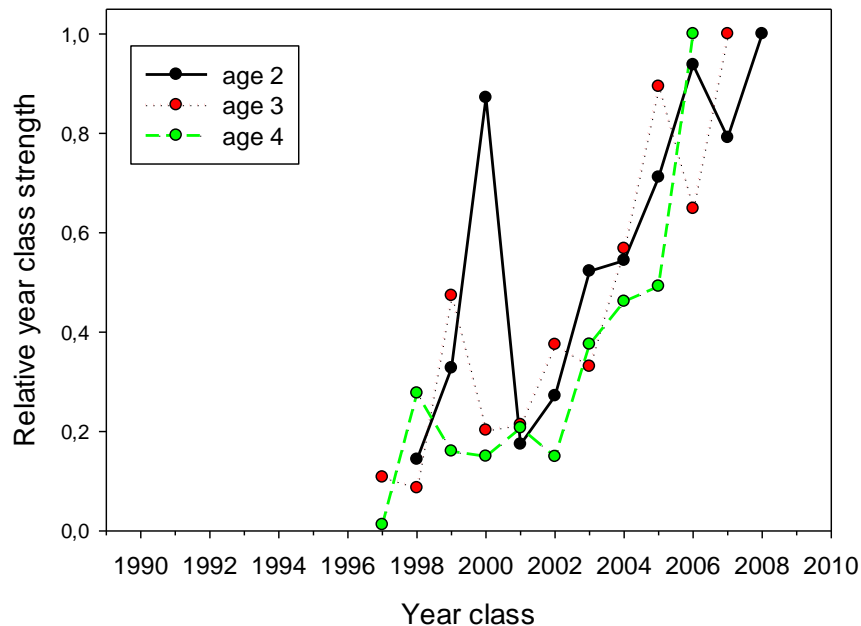
Stock biomass above all limits

Are we sure about the eastern cod stock development ?

Relative year-class strength in eastern Baltic stock

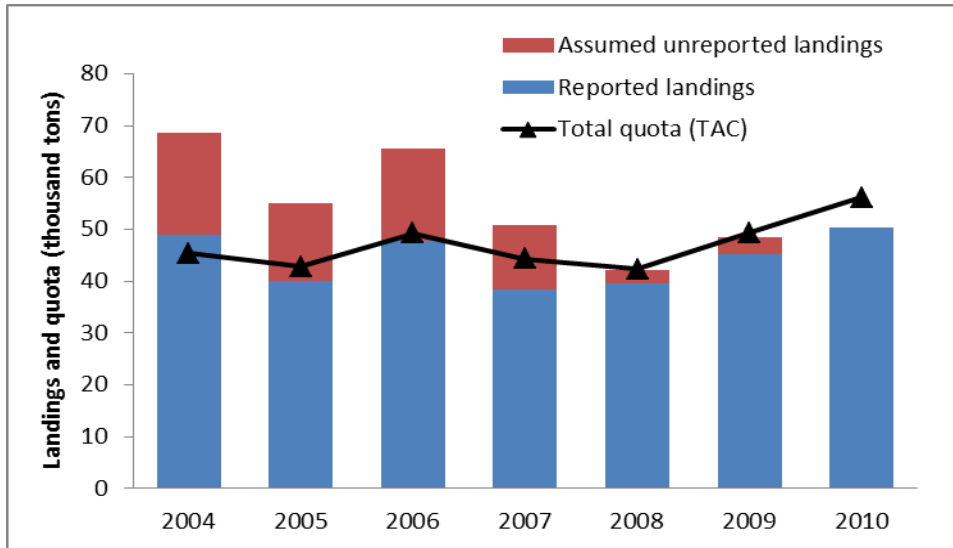


International bottom trawl surveys in February/March

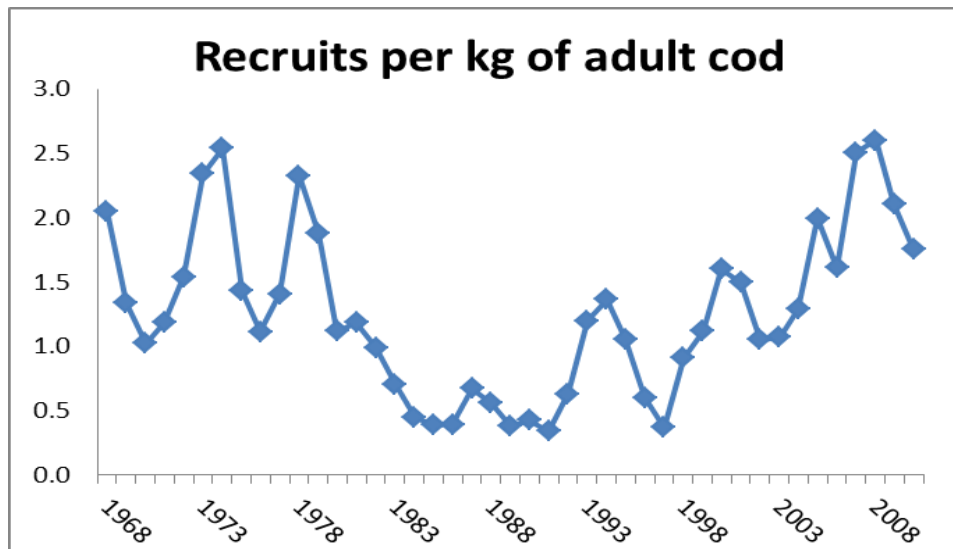


International bottom trawl surveys in November

What is driving the positive trend?



Decline in unreported catches

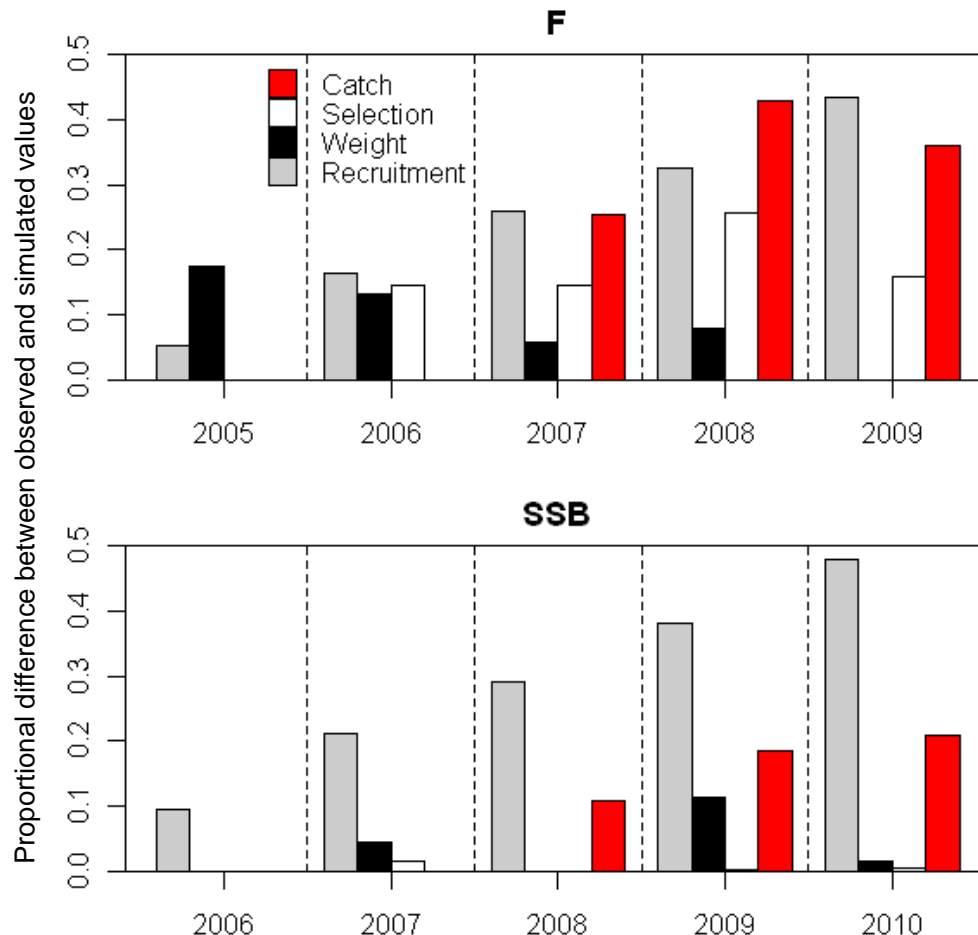


Increased recruitment production

Gear selection at age and weight at age have changed as well

What has reduced fishing mortality and increased the stock ?

Simulated effects of changes in different factors on decline in fishing mortality (F) and increase in spawning stock biomass (SSB).



Proportions how much F would have been higher and SSB lower if observed changes either in:

- catch (from 2007),
- recruitment (from 2005),
- selection pattern (from 2006)
- weight at age (from 2005)

would not have taken place.

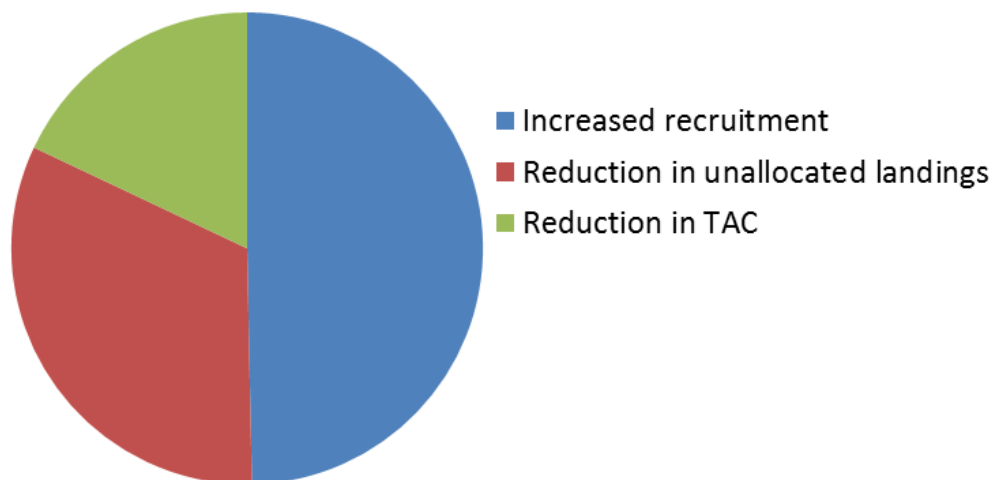
F is driven by catch reduction, recruitment and selection

SSB is to a larger extend driven by recruitment

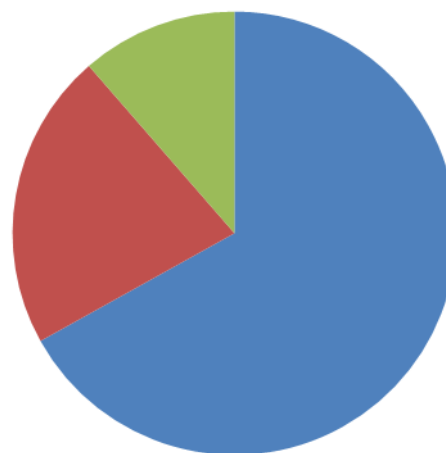
Management plan: reaching the target

Relative contribution to the decline in fishing mortality to below management target (in 2008), and to corresponding increase in biomass (in 2009)

Decline in fishing mortality

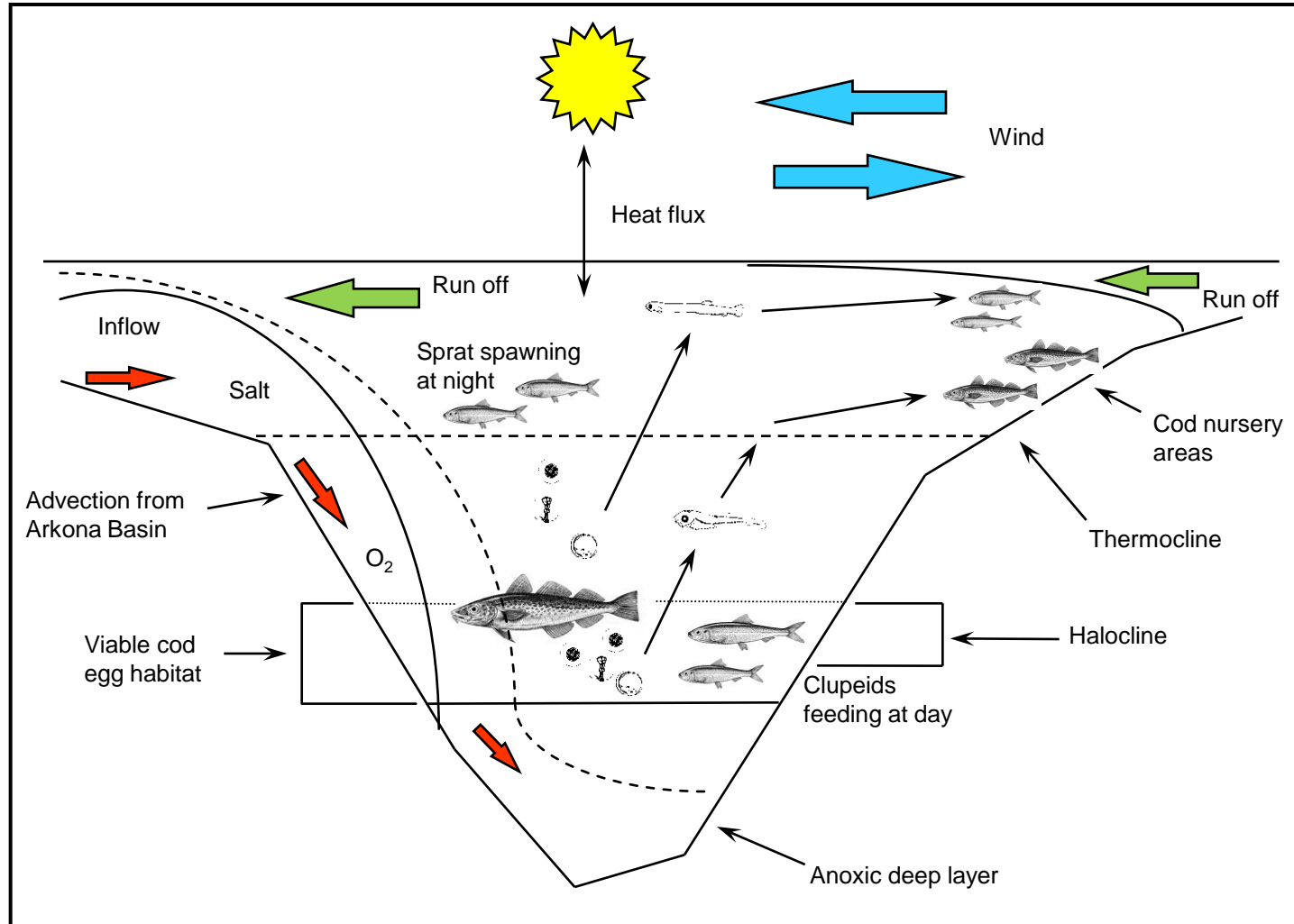


Increase in spawner biomass



What drives cod recruitment ?

Central Baltic basin as spawning area

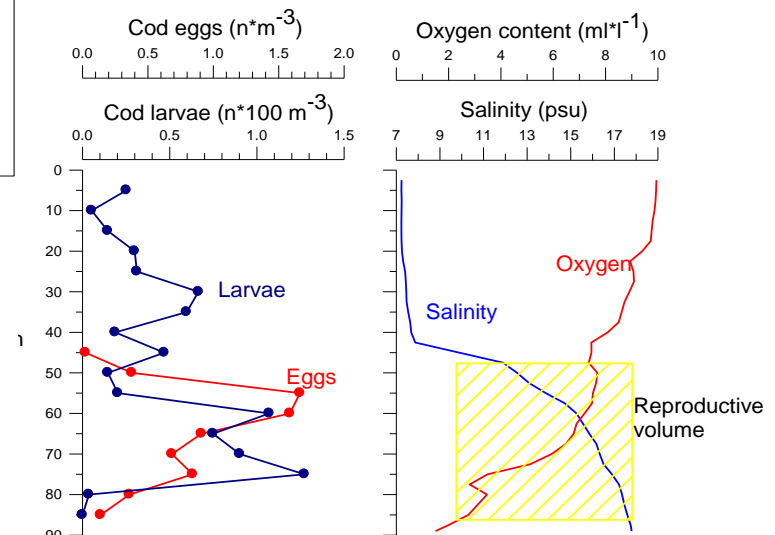
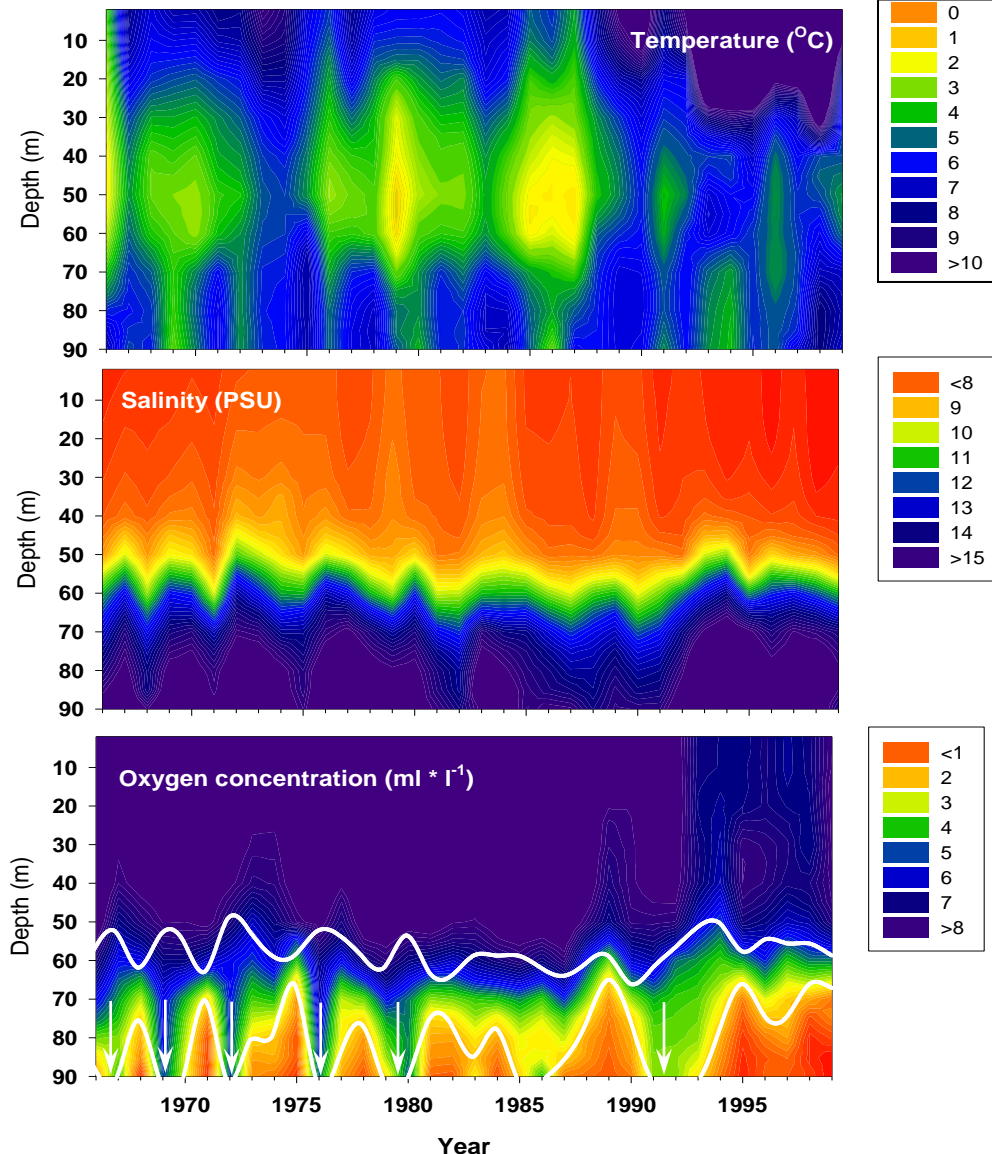


Spawning time: historically March to May, cod shifted in early 1990's to summer

Hydrography during cod spawning time

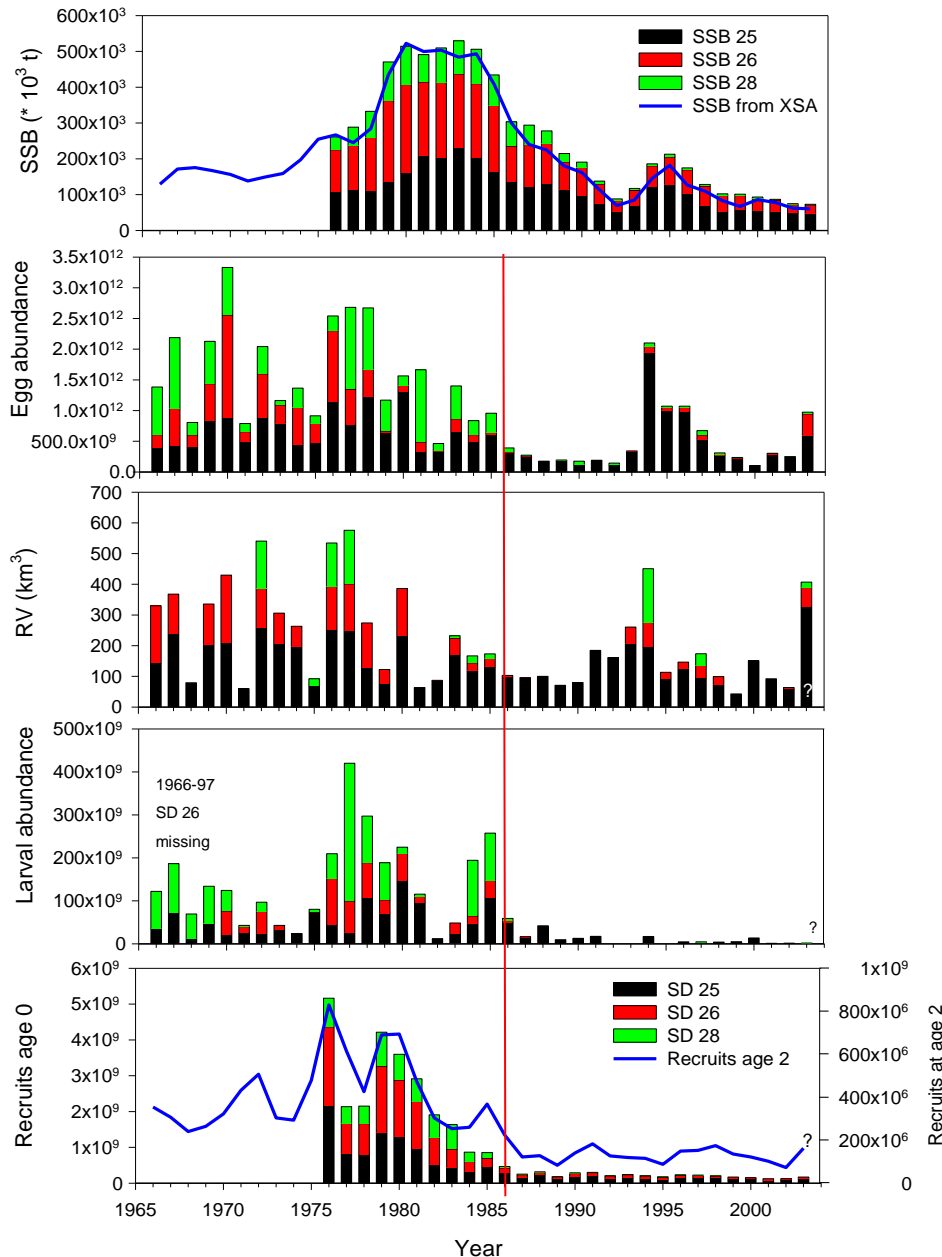
Bornholm Basin (SD 25) (2. and 3. quarter averages)

Red is dangerous for eggs:
 temperature $< 2^{\circ}\text{C}$ (no survival)
 salinity < 11 psu (no fertilisation)
 oxygen $< 2\text{ml/l}$ (no survival)



Reproductive volume
 characterised by sufficient
 oxygen in the bottom water,
 i.e. inflow years

Environmental impact on cod recruitment



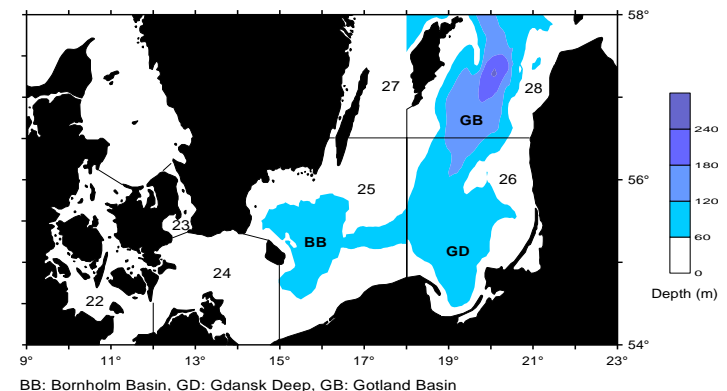
Very little spawning stock biomass (SSB) left in eastern spawning areas (SD 26 & 28)

Egg abundance very low in eastern areas since 1986

Reproductive volume is low in eastern areas since 1986; early 1990's an exception, but not utilised due to intermediate oxygen depletion

Larval abundance very low in all areas from 1987-2003. **Other processes act**

Spawning areas of cod (and sprat)



Environmental impact on cod recruitment

First order controlling factors

- 1) Stagnation, i.e. loss of 2 spawning areas in the 1980's, caused by lack of major Baltic inflows and eutrophication, i.e. reduced salinity and oxygen (Köster et al. 2003)
- 2) Prey availability for first feeding larvae, i.e. decline in marine copepod during the 1990's, caused by reduced salinity and predation by sprat (Hinrichsen et al, 2002, Möllmann et al. 2005)

Second order regulating factors

- 3) Egg predation by sprat and herring especially in 1980's, depending on salinity/oxygen and timing of spawning defining vertical and horizontal overlap between predator and prey, respectively (Köster and Möllmann 2000a)
- 4) Prey availability affects egg production by adult stock, depending on sprat stock dynamics (has increased in 1990's) (Kraus et al. 2002)
- 5) Cod cannibalism, depending on transport of juveniles, temperature and oxygen defining horizontal overlap to adults (has decreased through 1980's) as well as abundance of alternative prey (has increased during 1990's) (Neuenfeldt and Köster 2000)

Environmental impact on sprat recruitment

First order effects

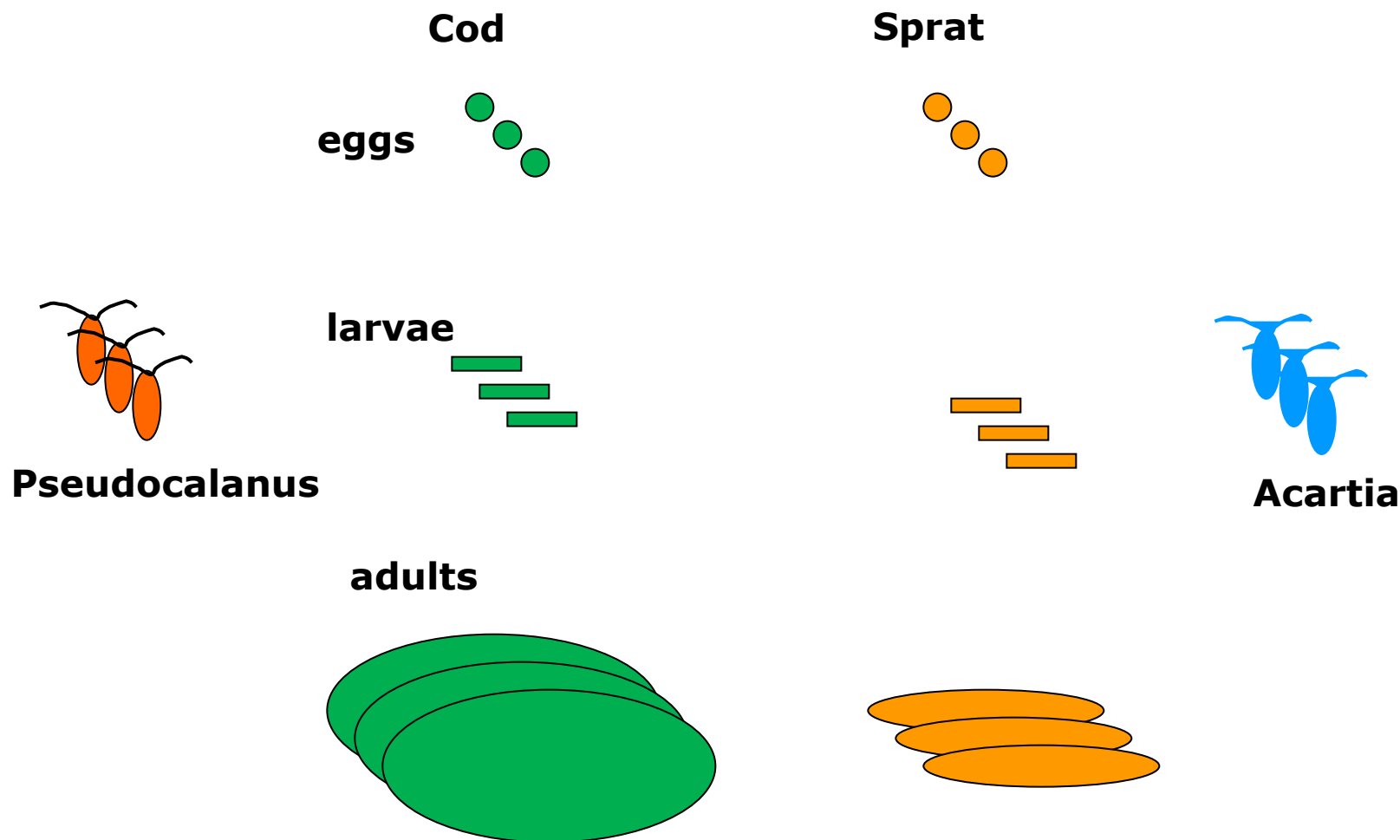
- 1) Temperature increase in the winter water (enhanced egg production and egg survival)
(Köster et al. 2003)
- 2) Increase in prey availability for larvae (secondary effect of high temperatures)
(Voss et al. 2011)
- 3) Transport pattern (staying in deeper water areas of advantage, situation has increased)
(Baumann et al. 2006)

Second order effect

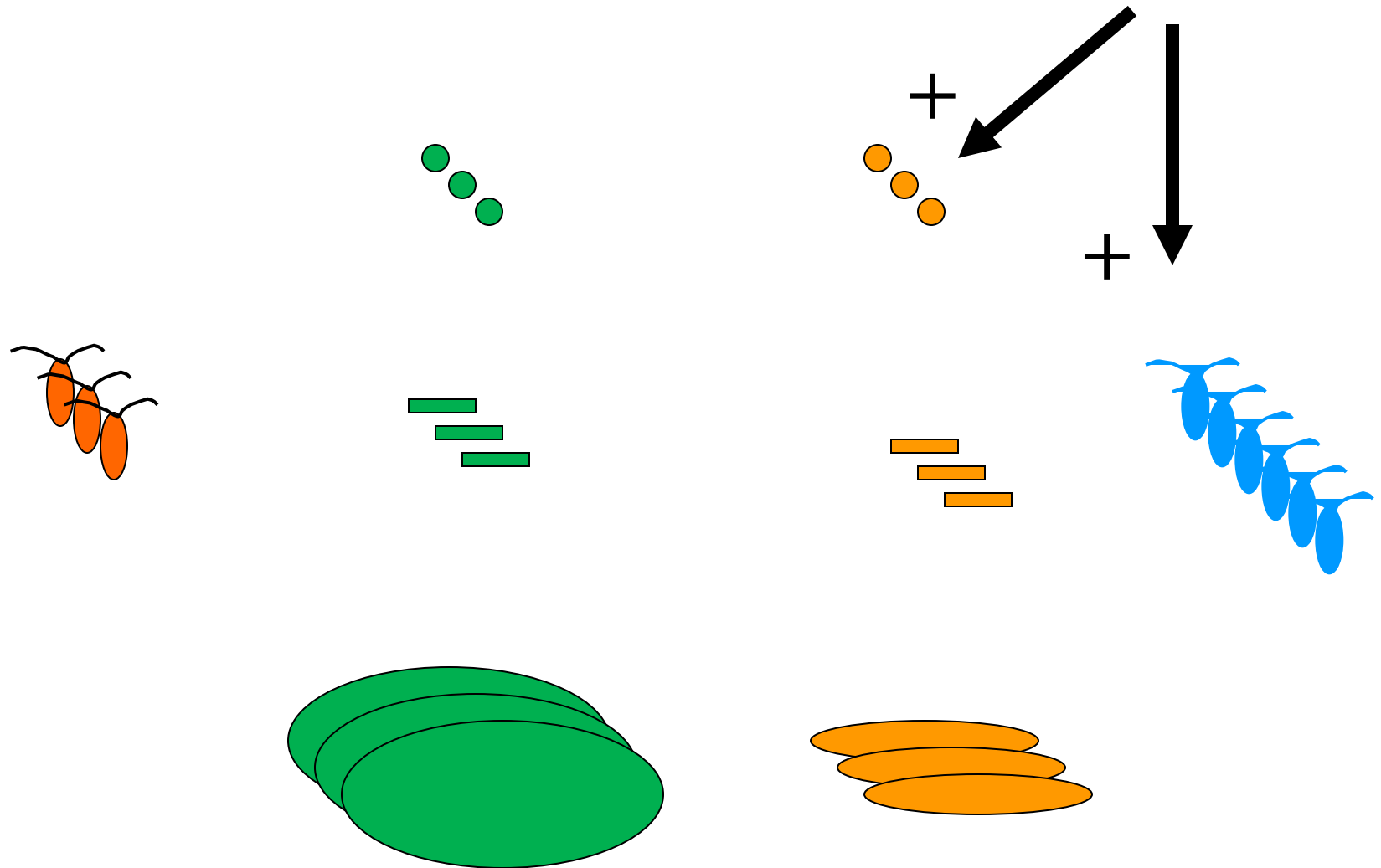
- 4) Decline in predation pressure by cod
(e.g. Sparholt 1994)
- 5) Egg cannibalism (same principal as for cod eggs)
(Köster et al. 2000b)

Linking climate, copepods and fish recruitment ... a simplified sketch !

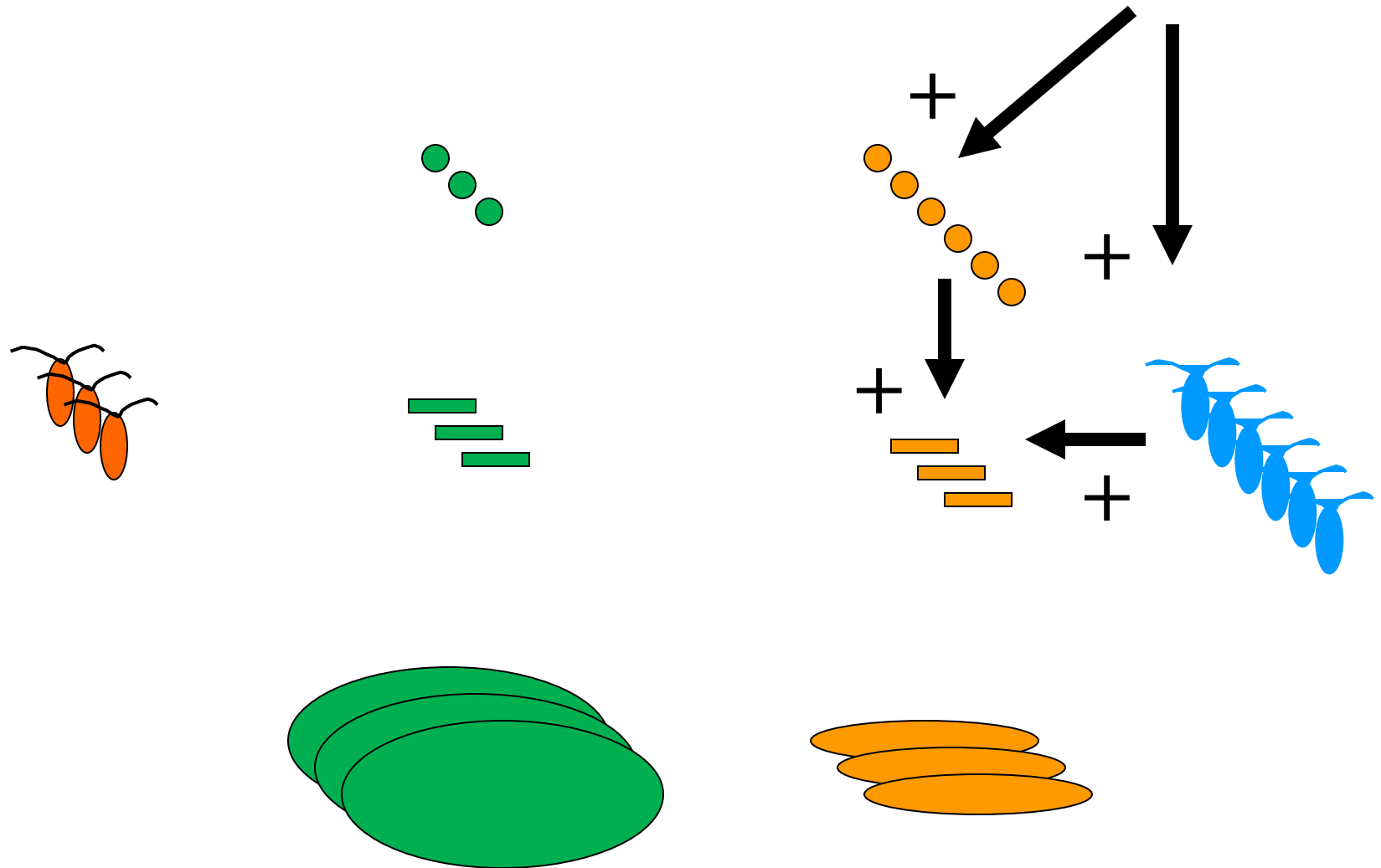
Actors:



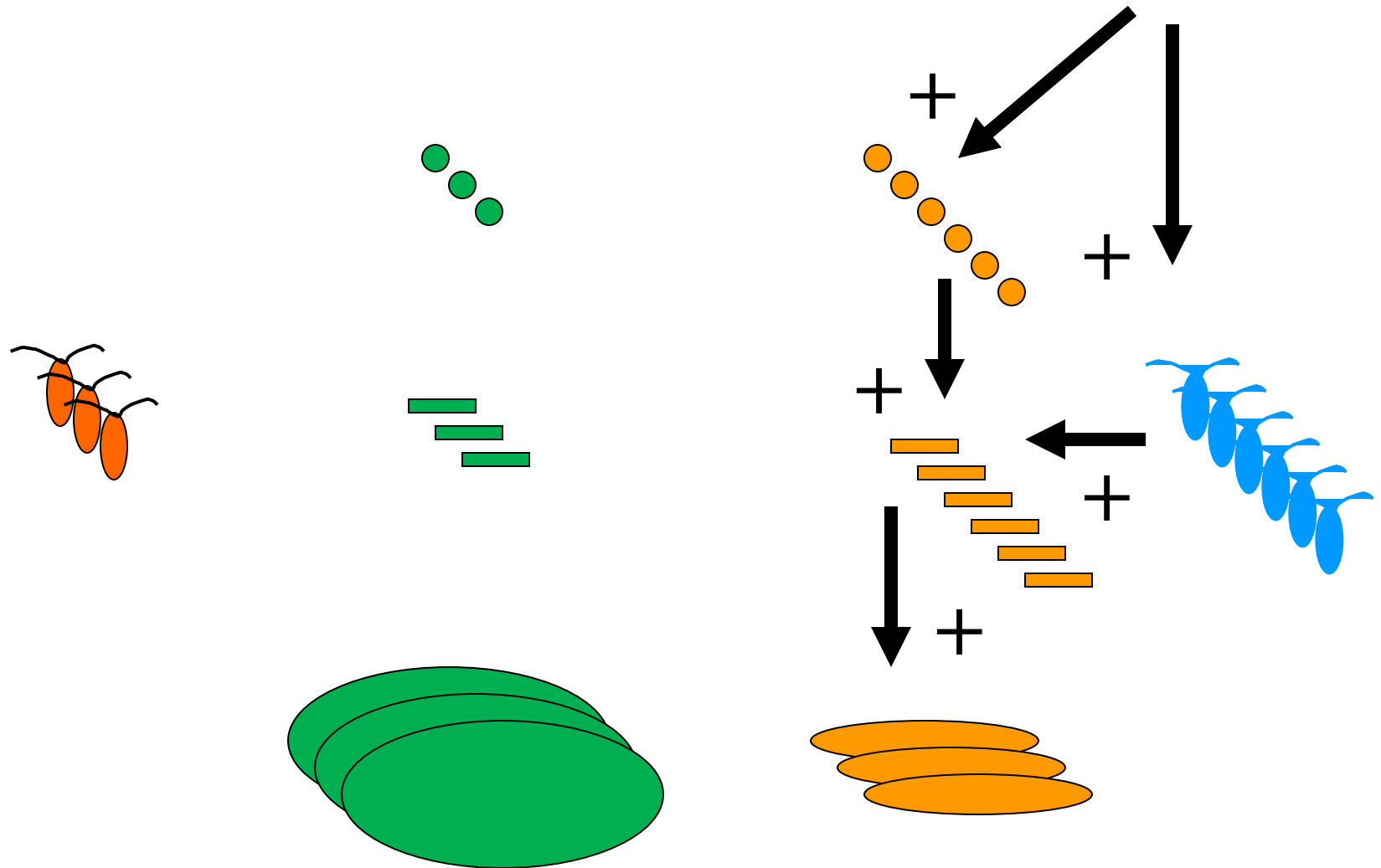
Mild winters



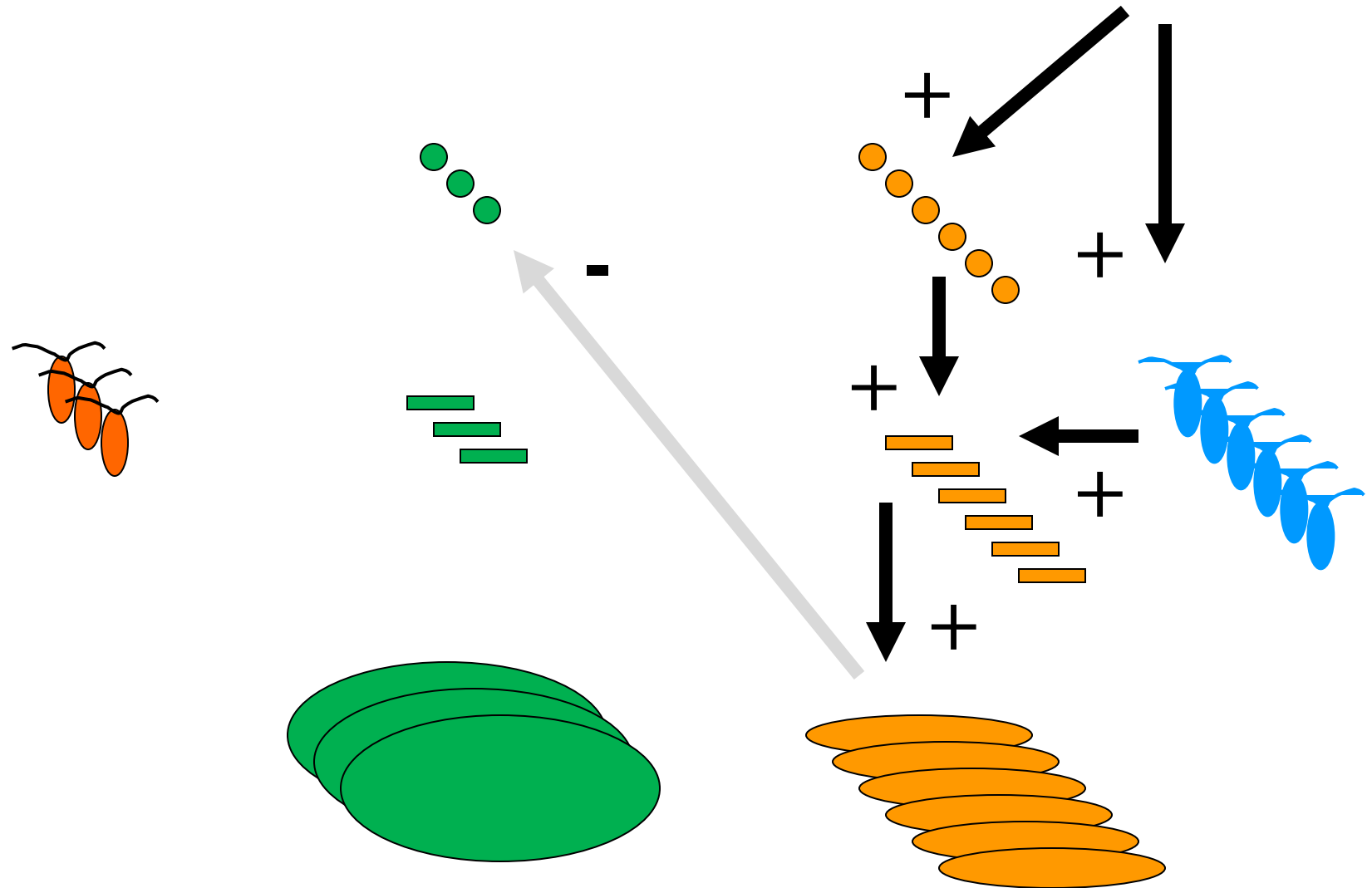
Mild winters



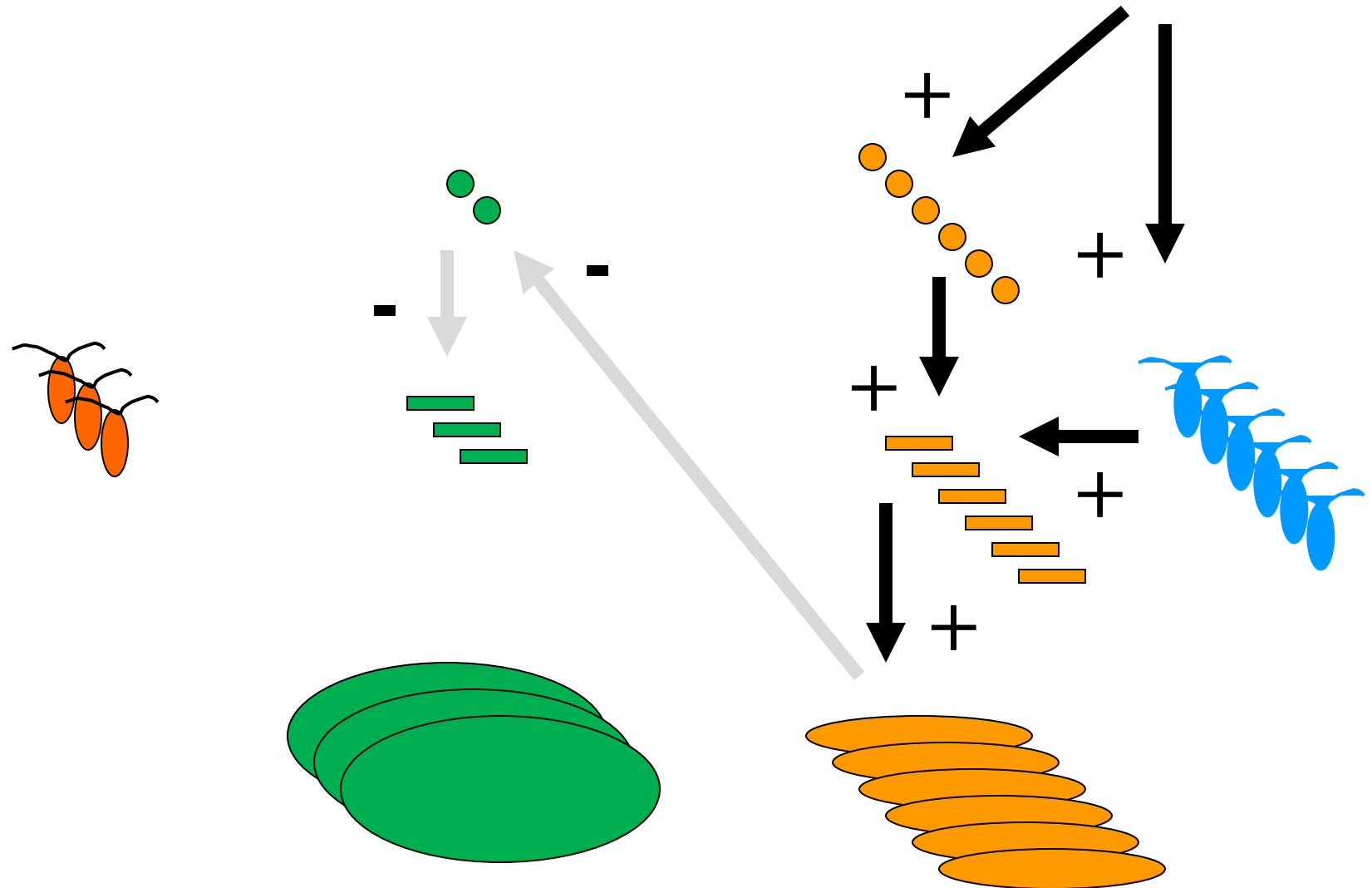
Mild winters



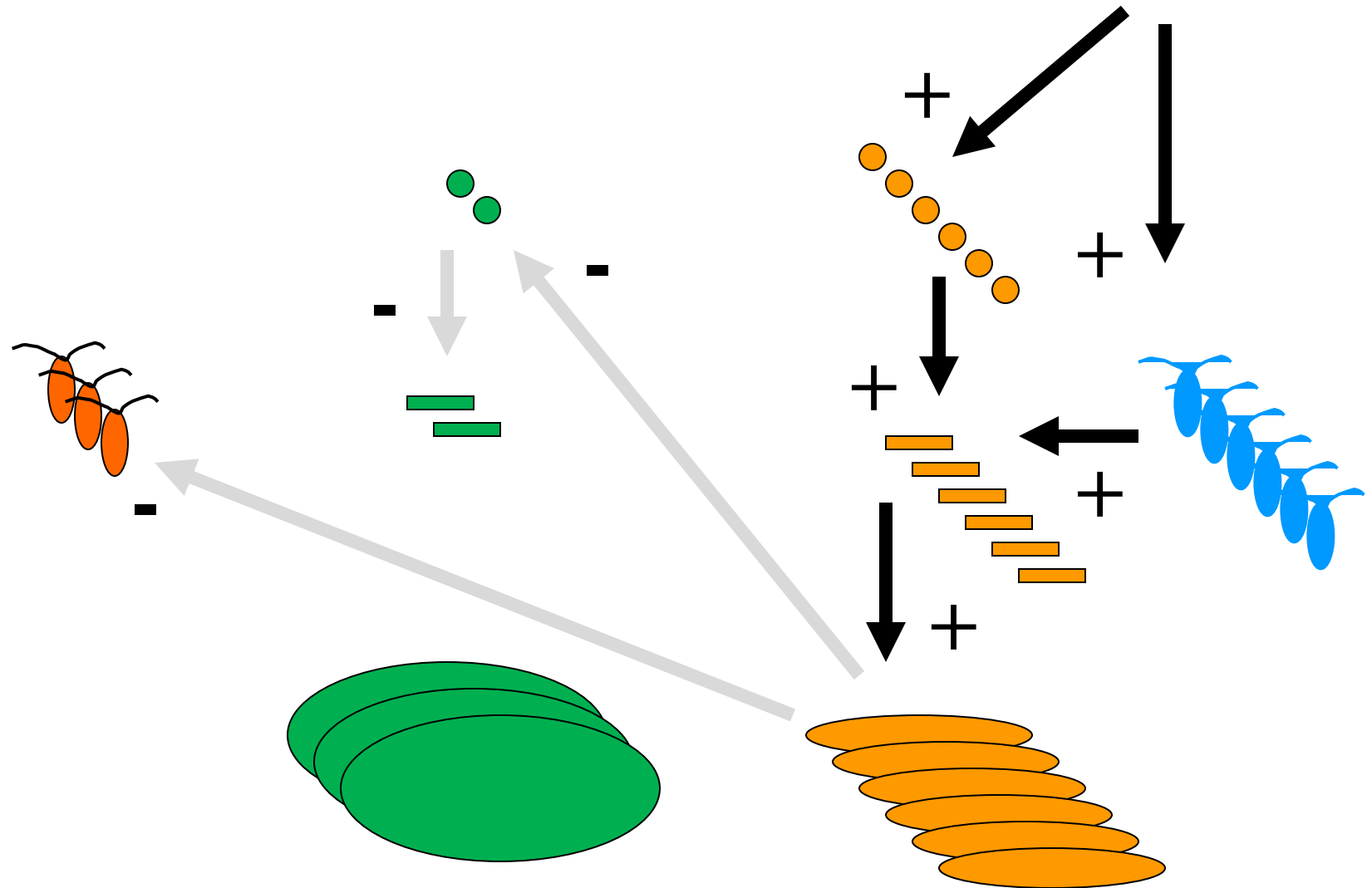
Mild winters



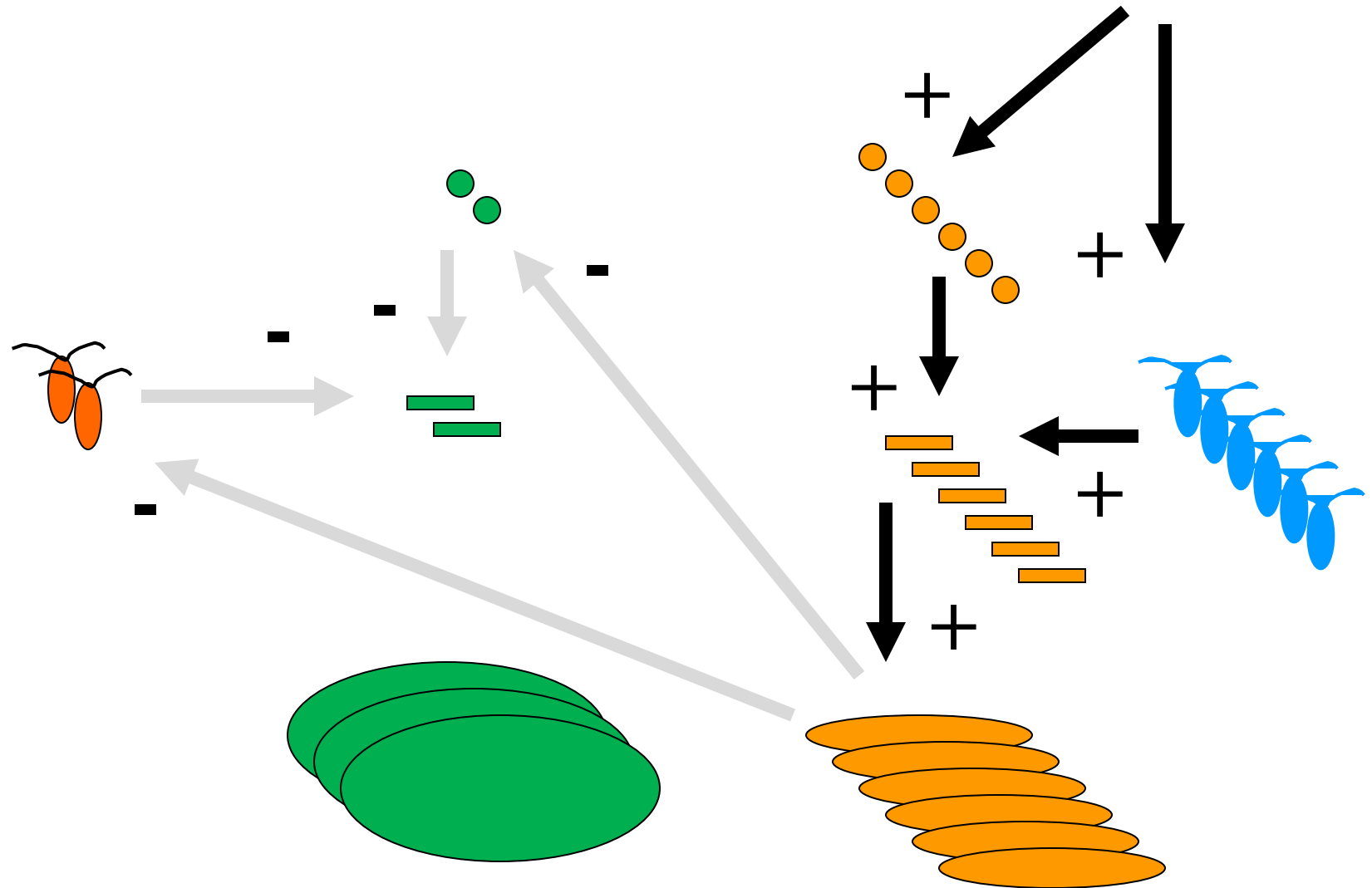
Mild winters



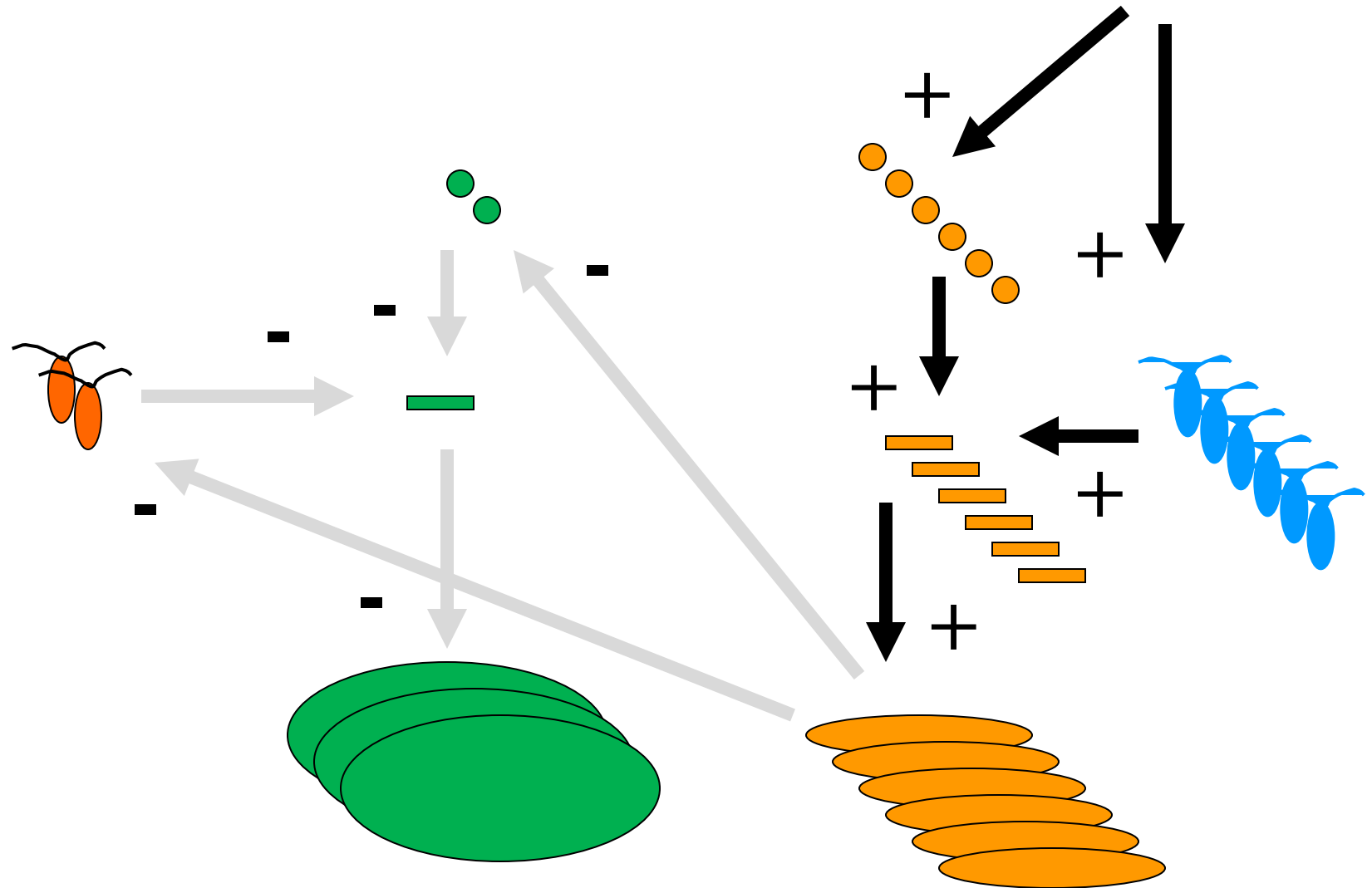
Mild winters

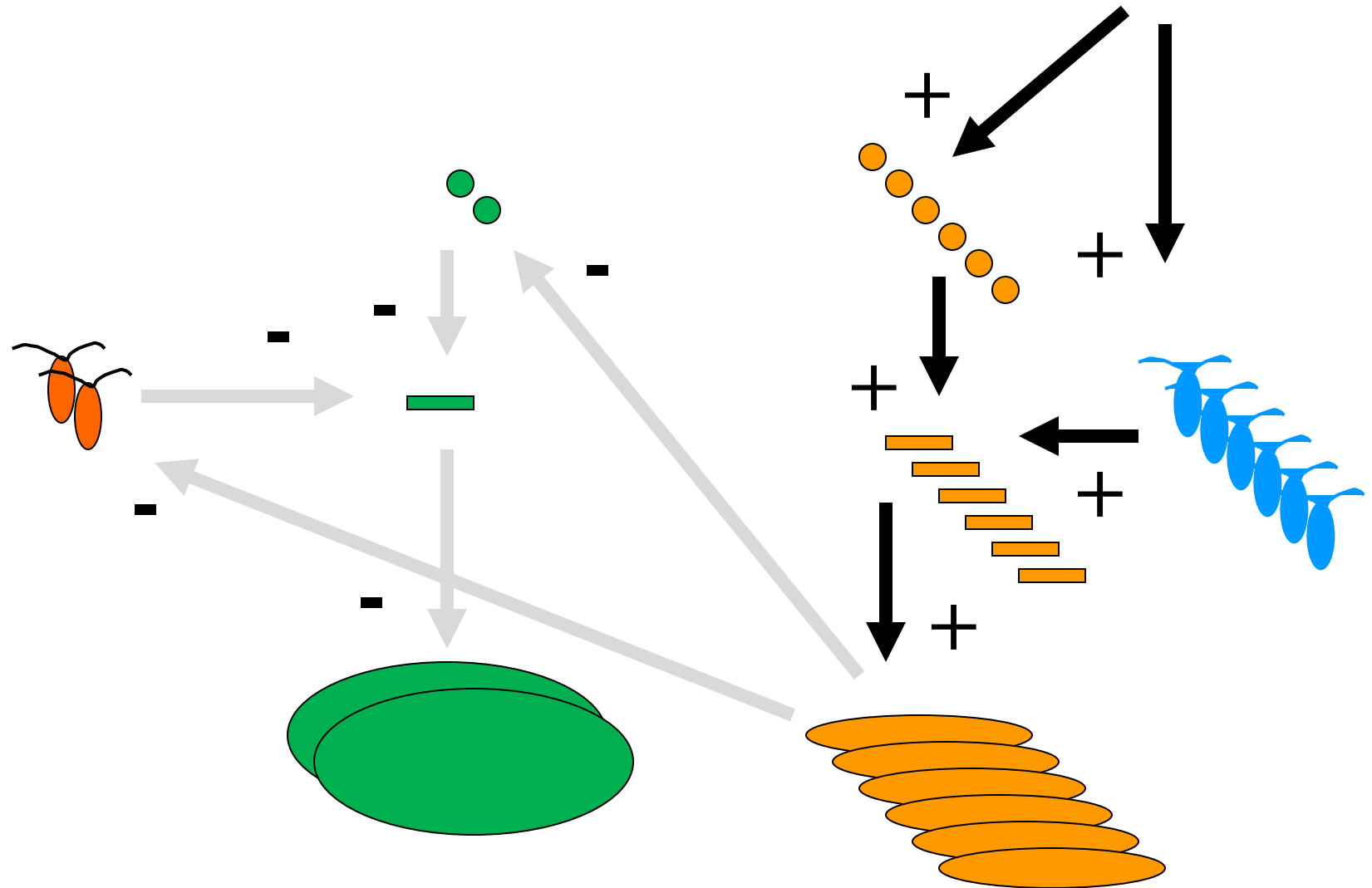


Mild winters



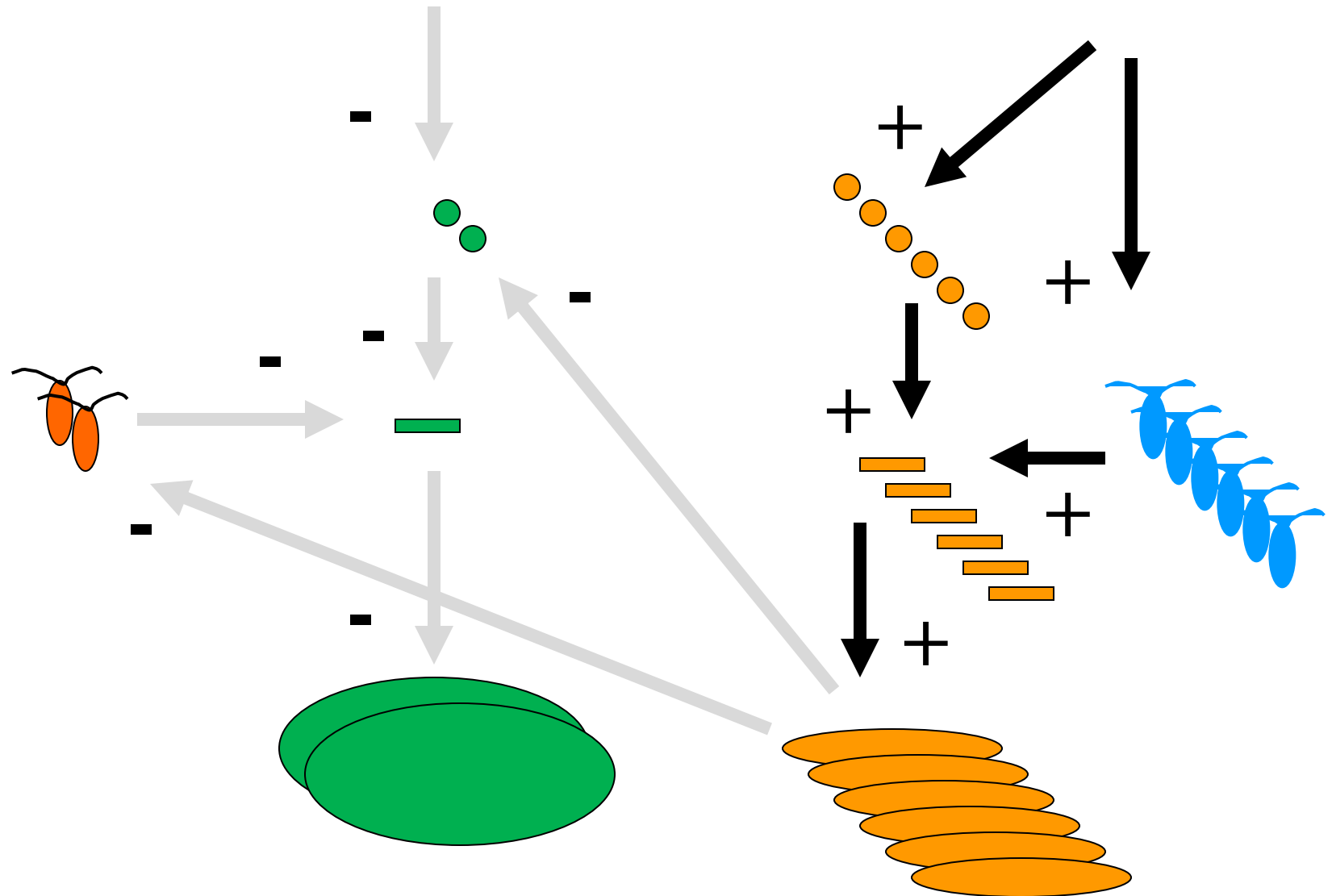
Mild winters





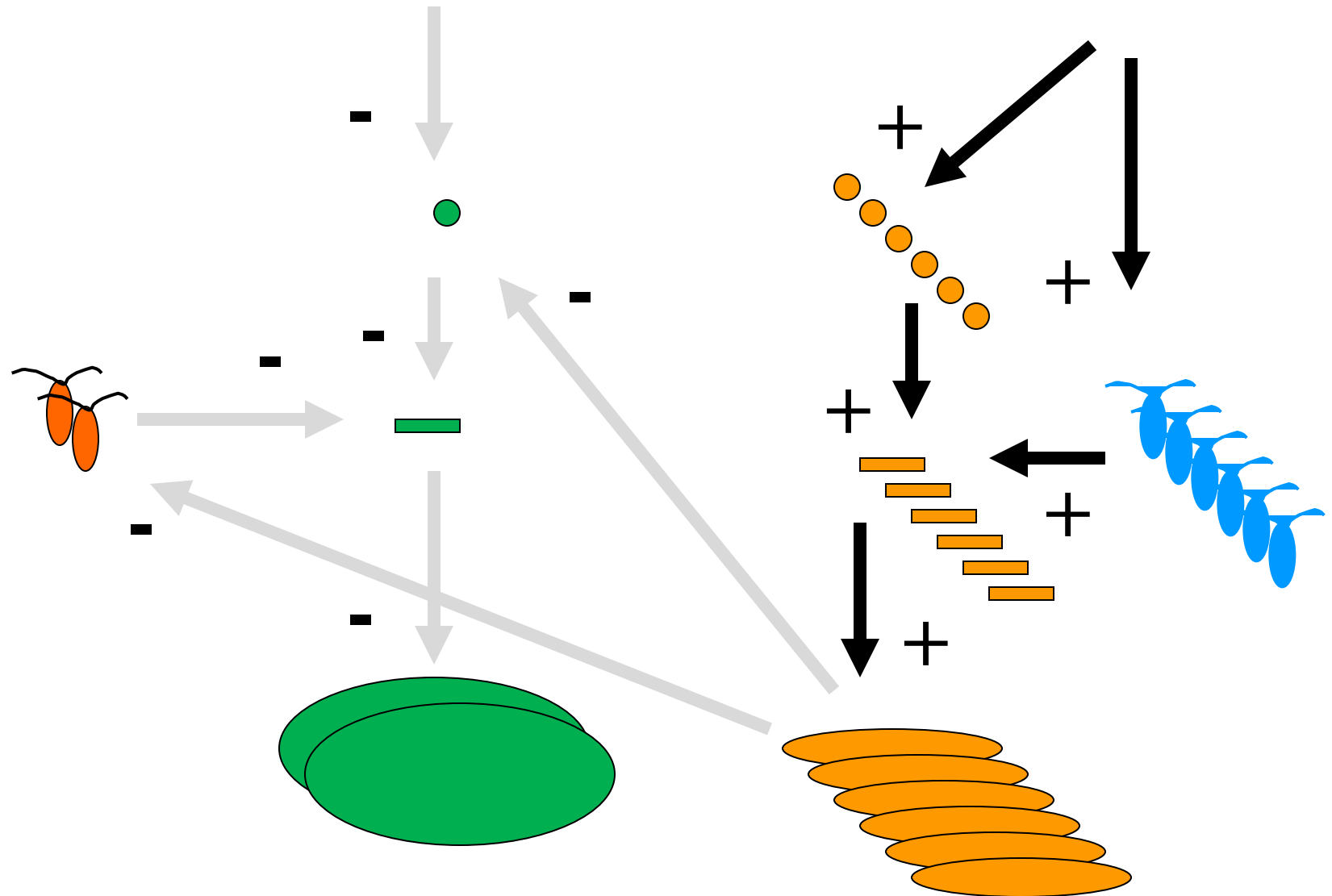
Stagnation

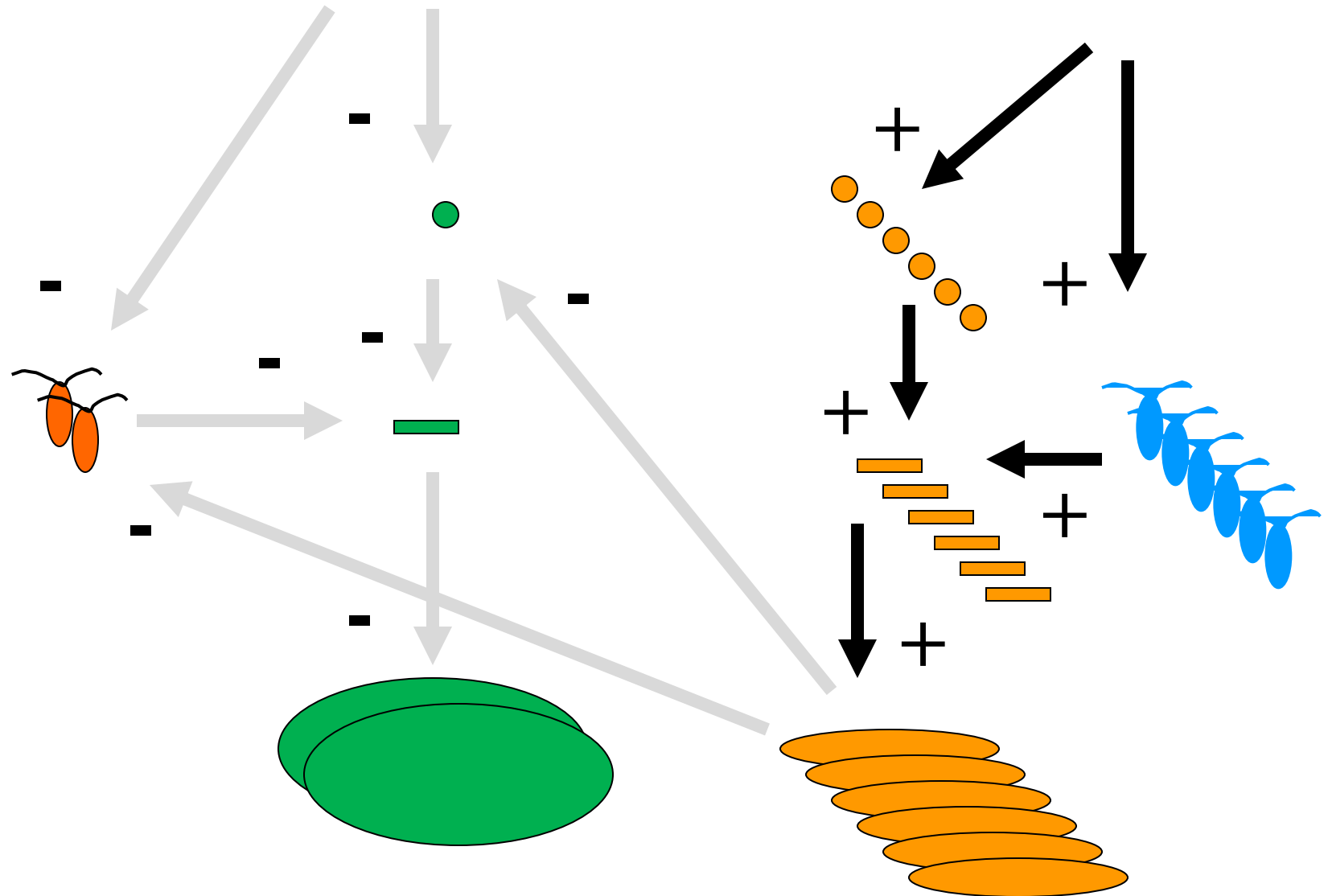
Mild winters



Stagnation

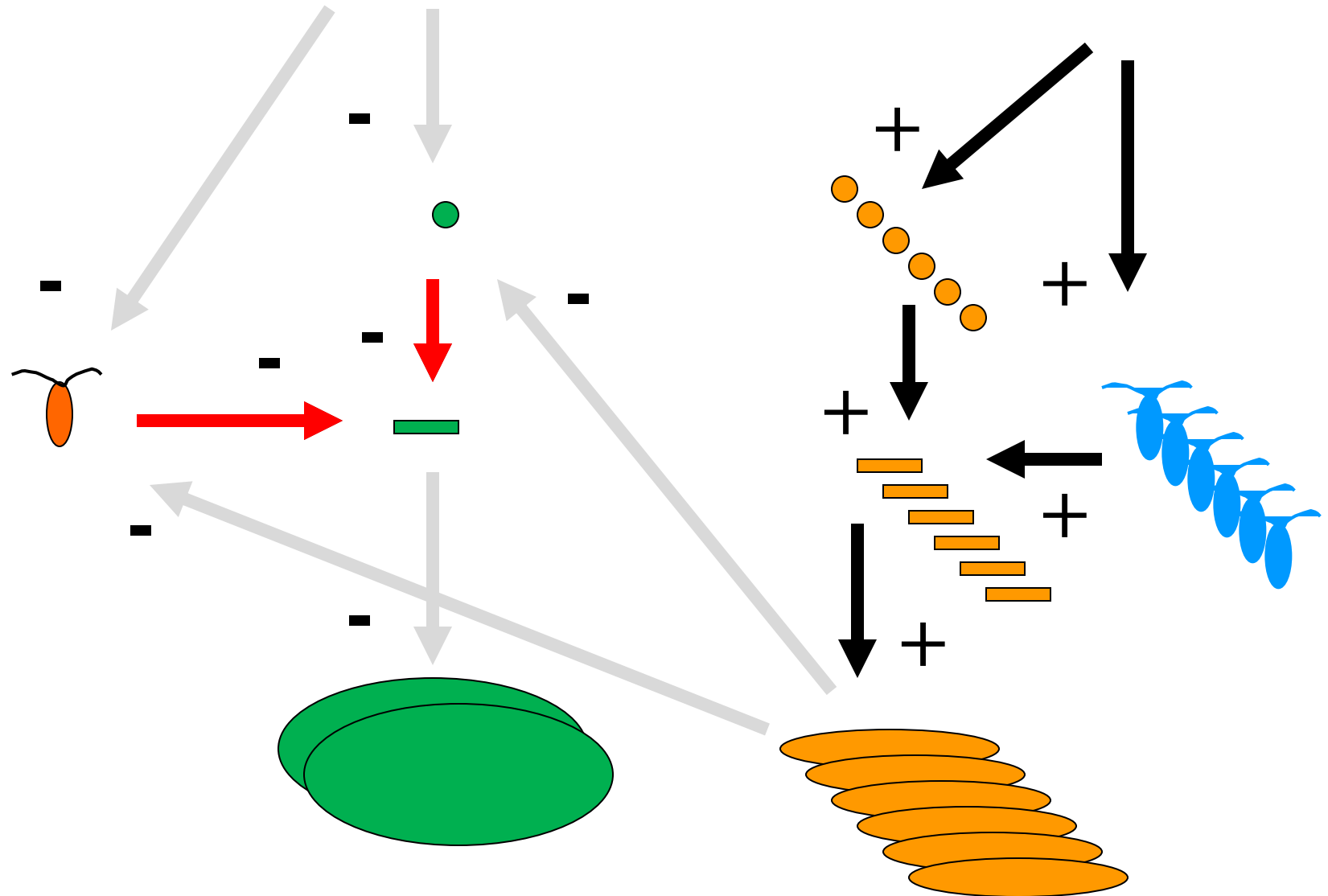
Mild winters





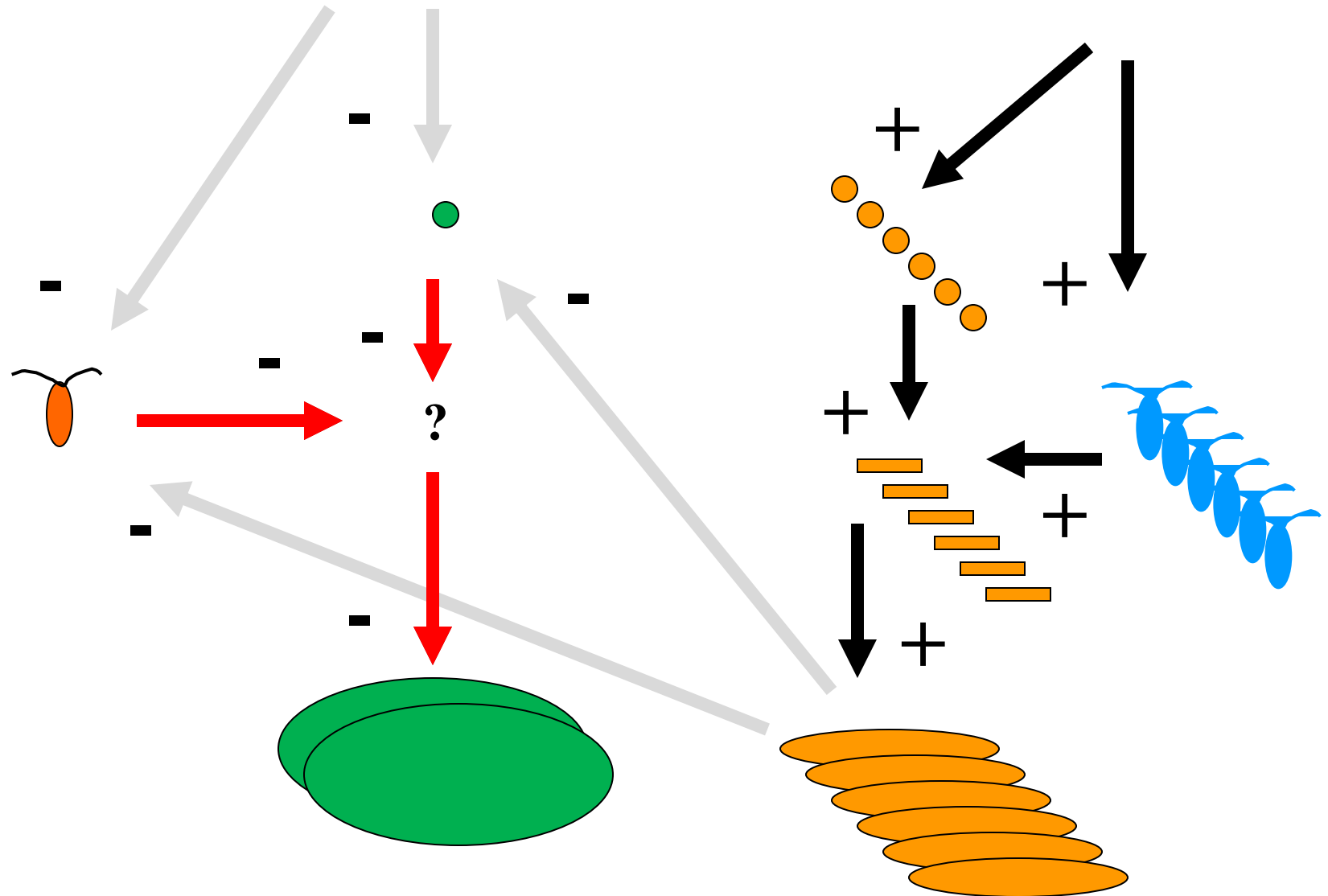
Stagnation

Mild winters

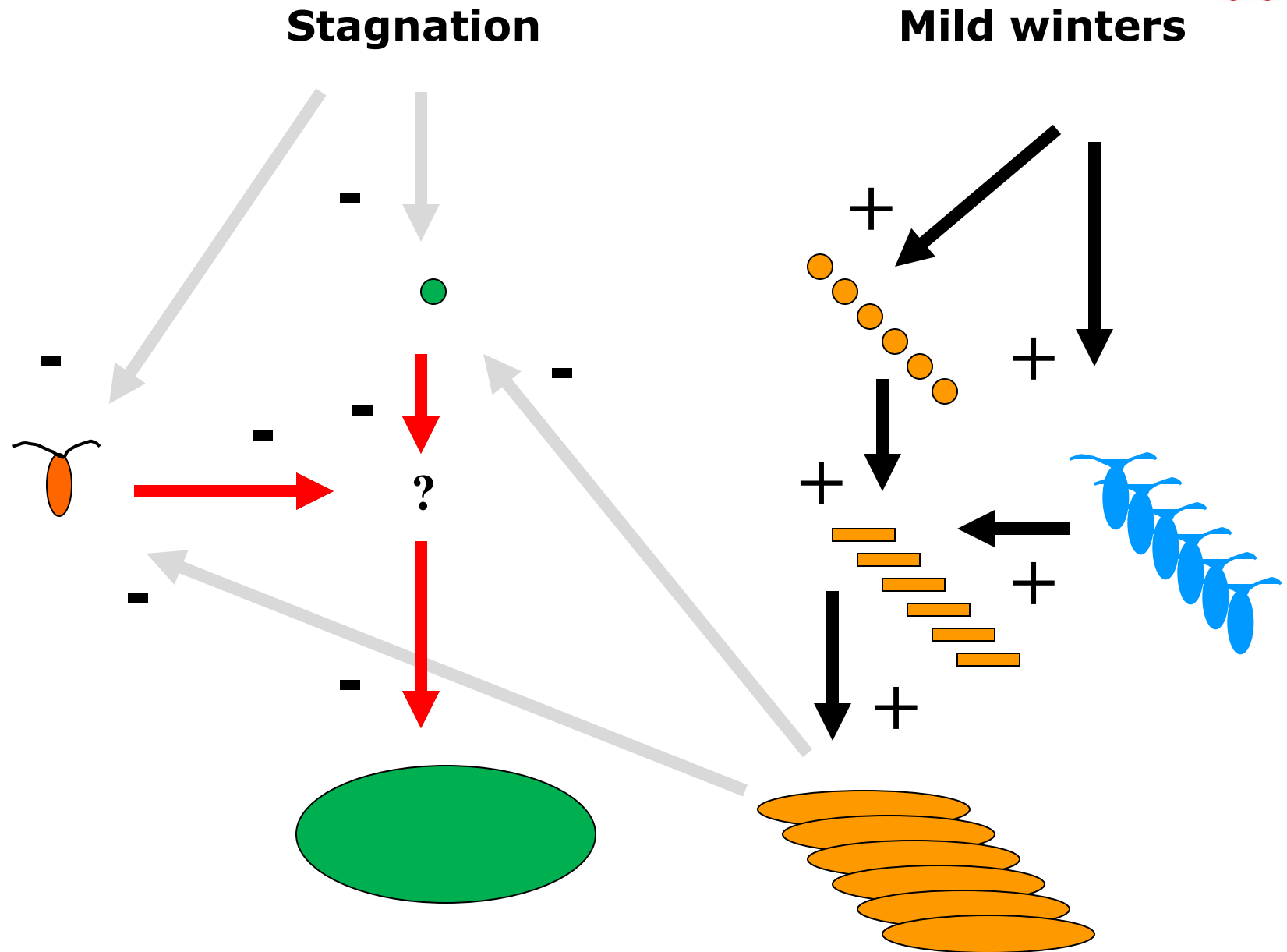


Stagnation

Mild winters



Situation in early 2000's

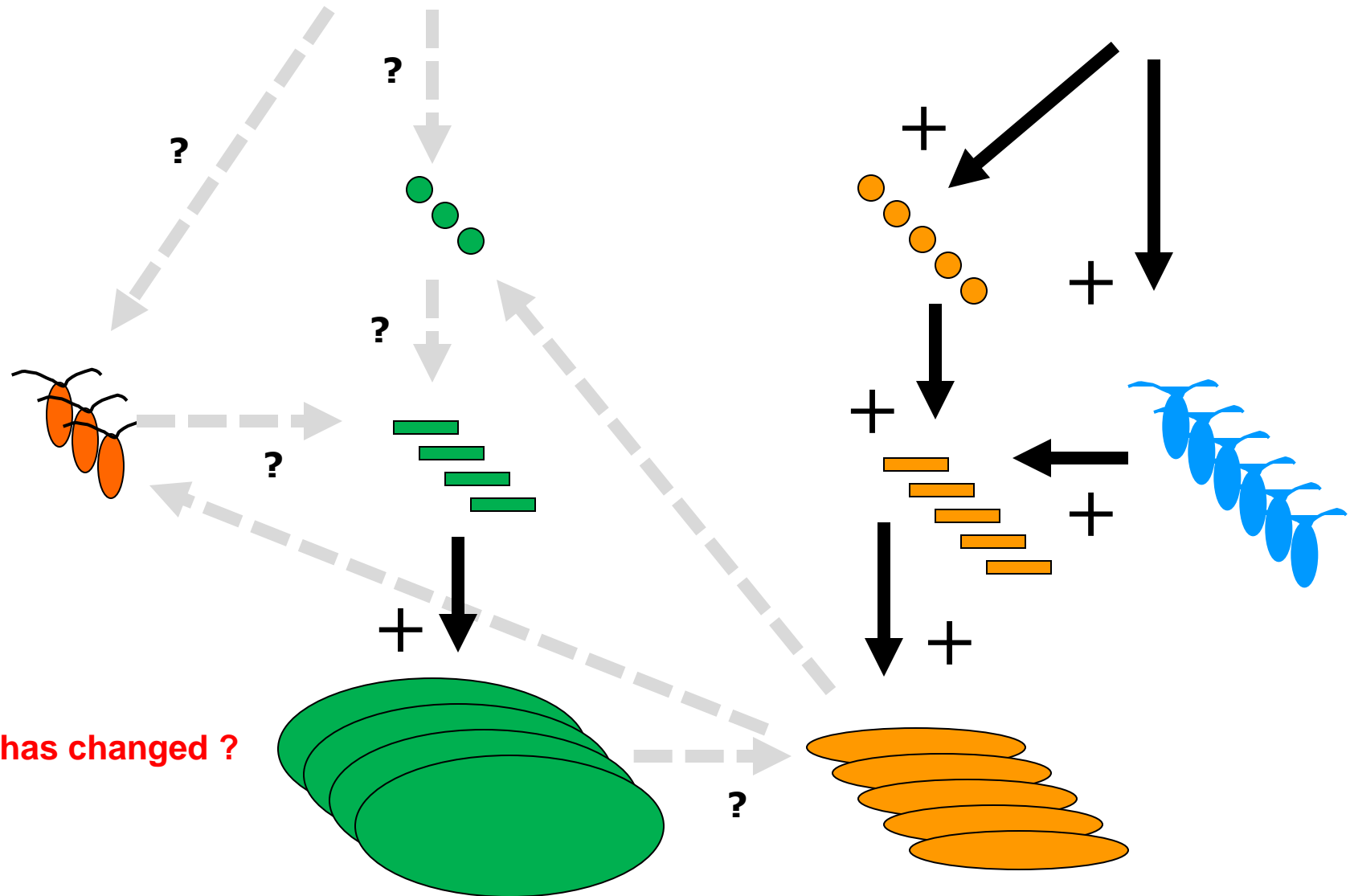


Situation in late 2000's

Stagnation

Mild winters

What has changed ?



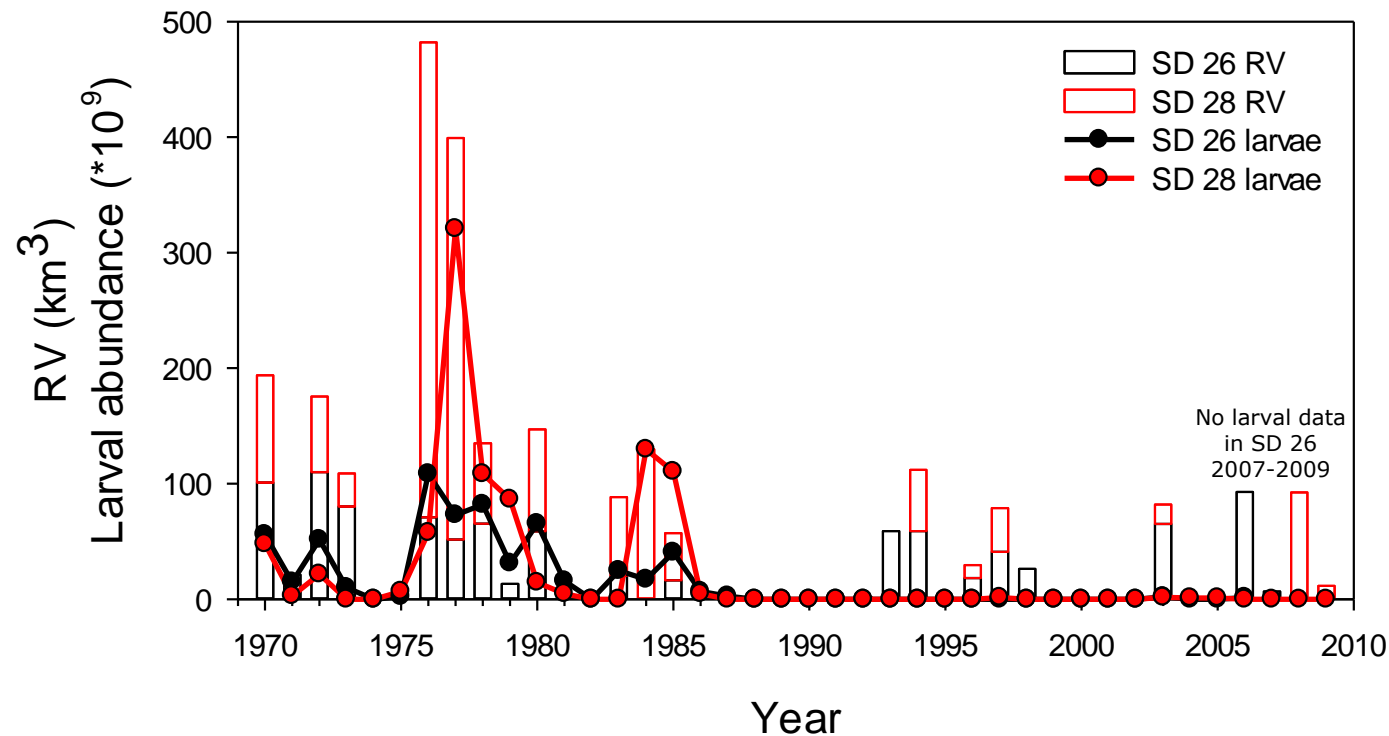
What is different now ?

First order controlling factors

- 1) Stagnation, i.e. loss of 2 spawning areas in the 1980's, caused by lack of major Baltic inflows and eutrophication, i.e. reduced salinity and oxygen
- What about hydrography, has that changed ?

Hydrography in eastern spawning areas

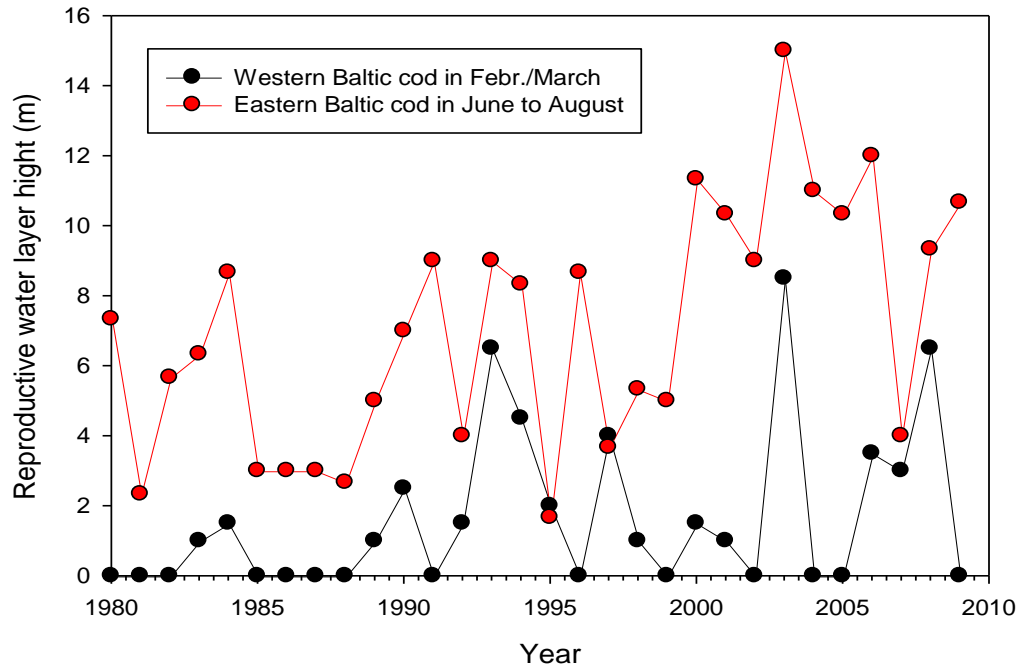
Reproductive volume and larval abundances in Gdansk Deep and Gotland Basin



Nothing new in the east !

Something new in the west !

Increasing spawning activity of Eastern Baltic cod in the Arkona Basin

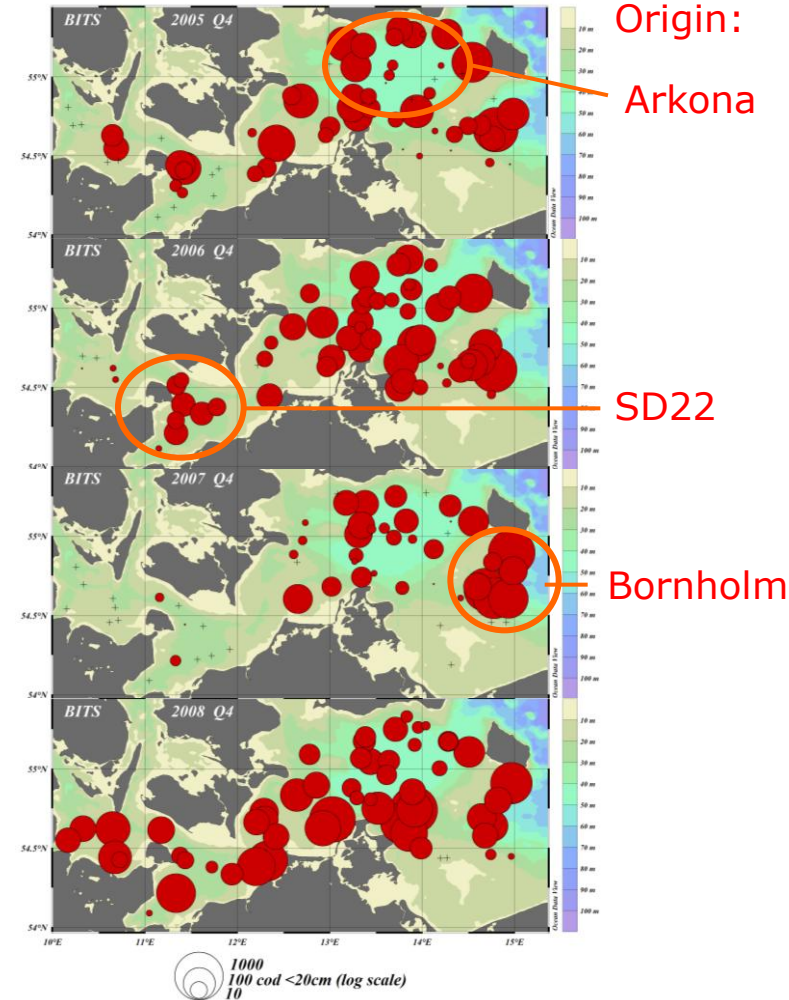


Suitable spawning layer for eastern cod ca. 10 m in all years since 2000 (except 2007)

Contributes to Eastern stock recruitment, but magnitude uncertain

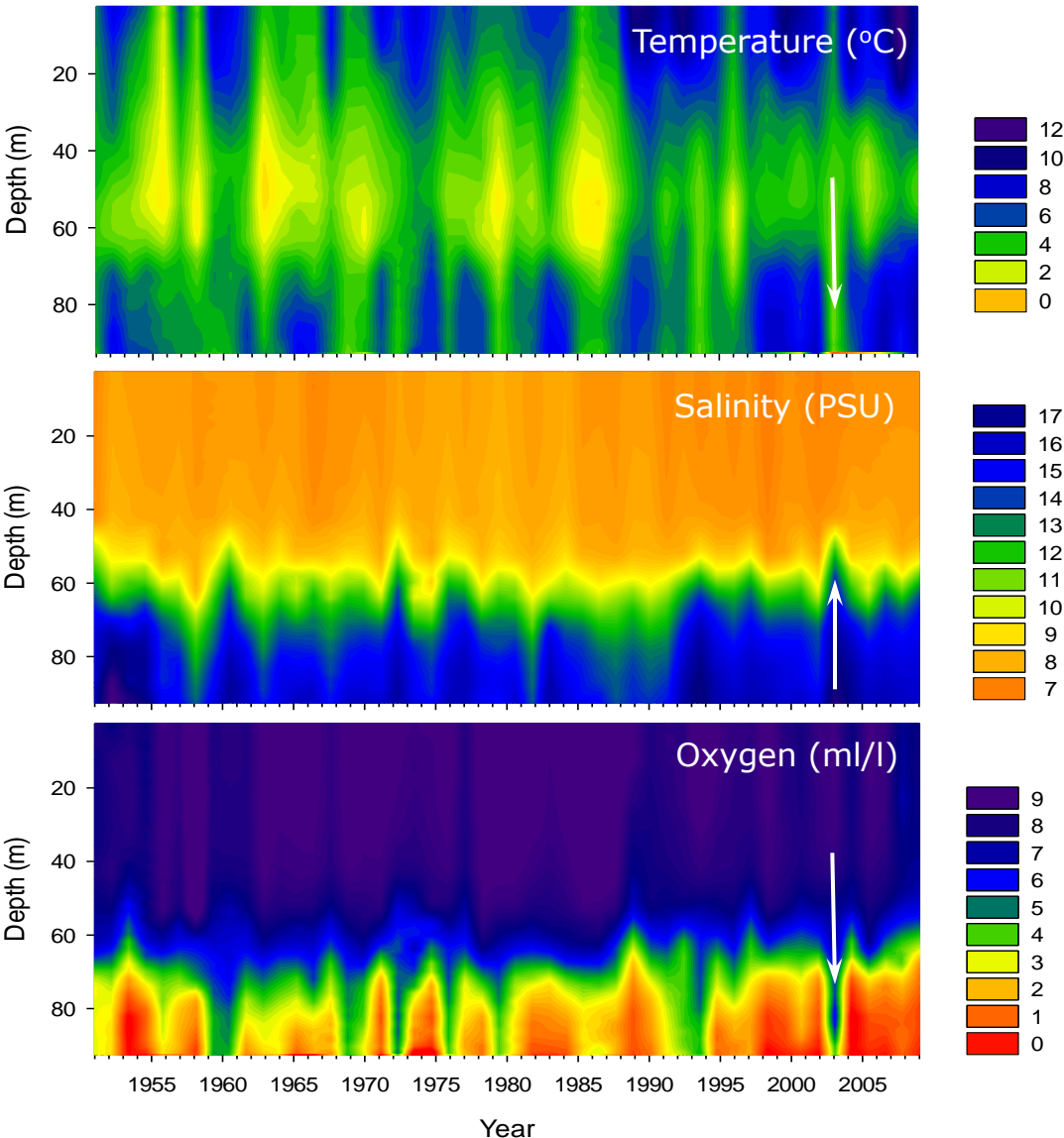
High recruitment also in 2007, despite low RV and reduced 0-group abundance in SD 24

Bottom trawl catch rates of 0-group



Hydrography in Bornholm Basin

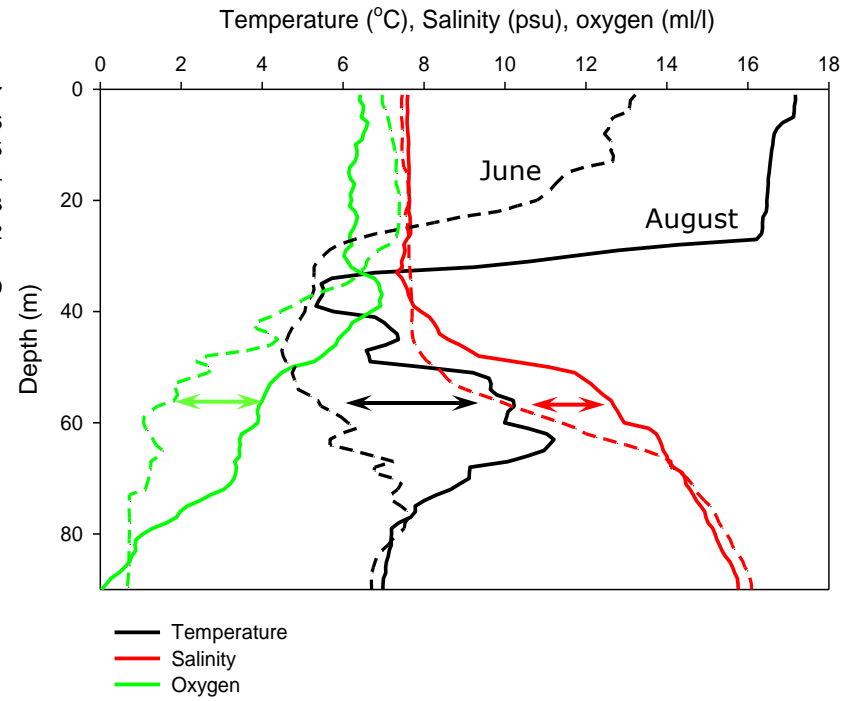
Hydrography in May: except for 2003 inflow pronounced stagnation



However, warm summer inflows (observed first time in 2002) enable egg survival:

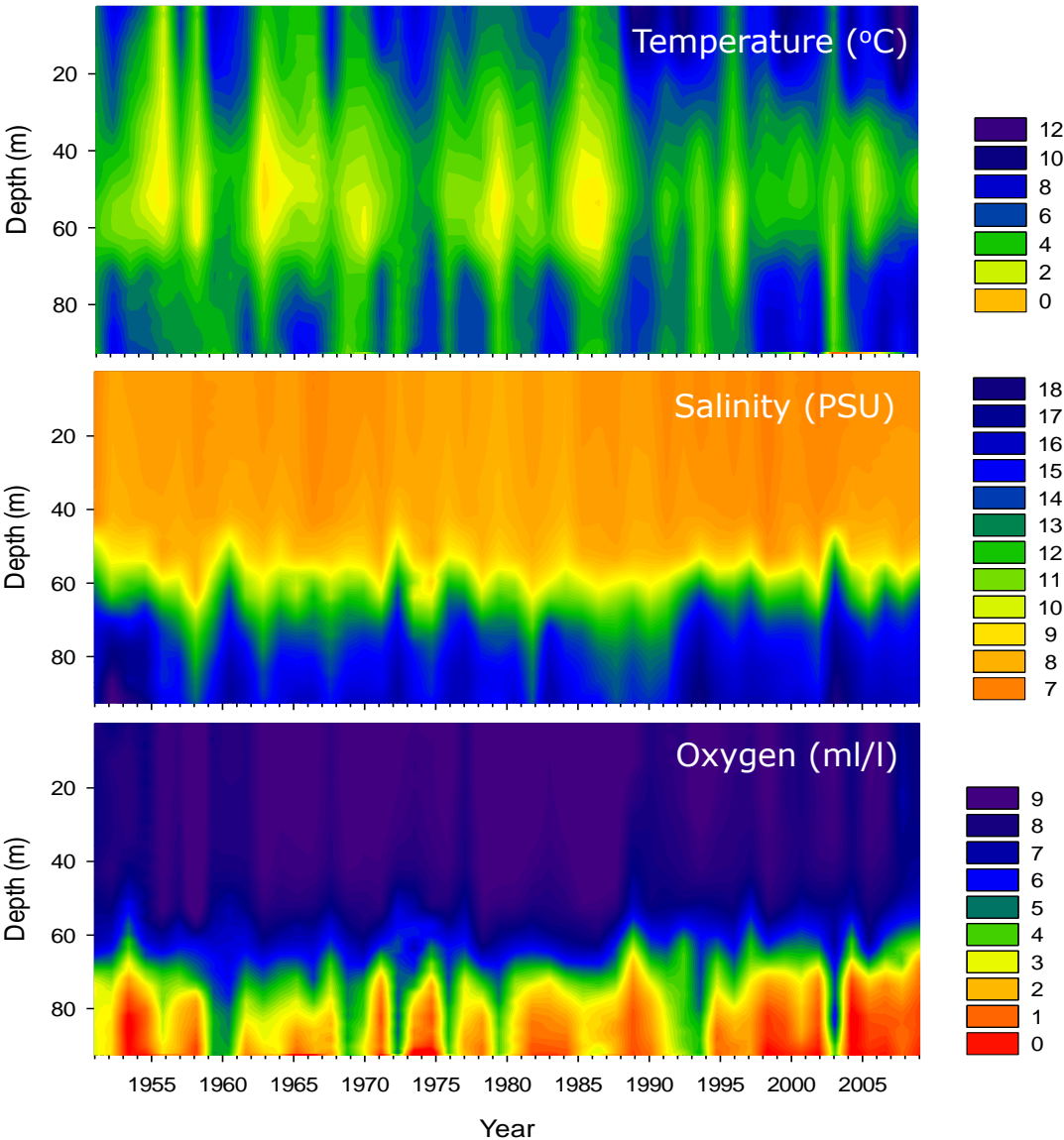
RV in June 2008: 0 m

RV in August 2008: 27 m



Hydrography in Bornholm Basin

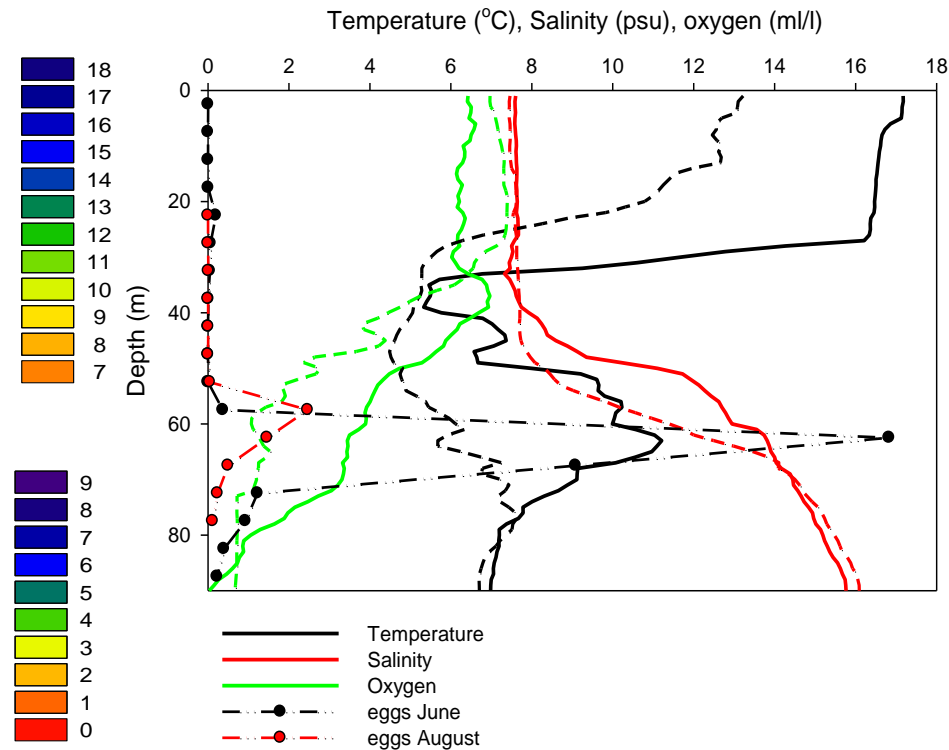
Hydrography in May: hampers egg survival more then before.



However, warm summer inflows (observed first time in 2002) enable egg survival:

RV in June 2008: 0 m

RV in August 2008: 27 m



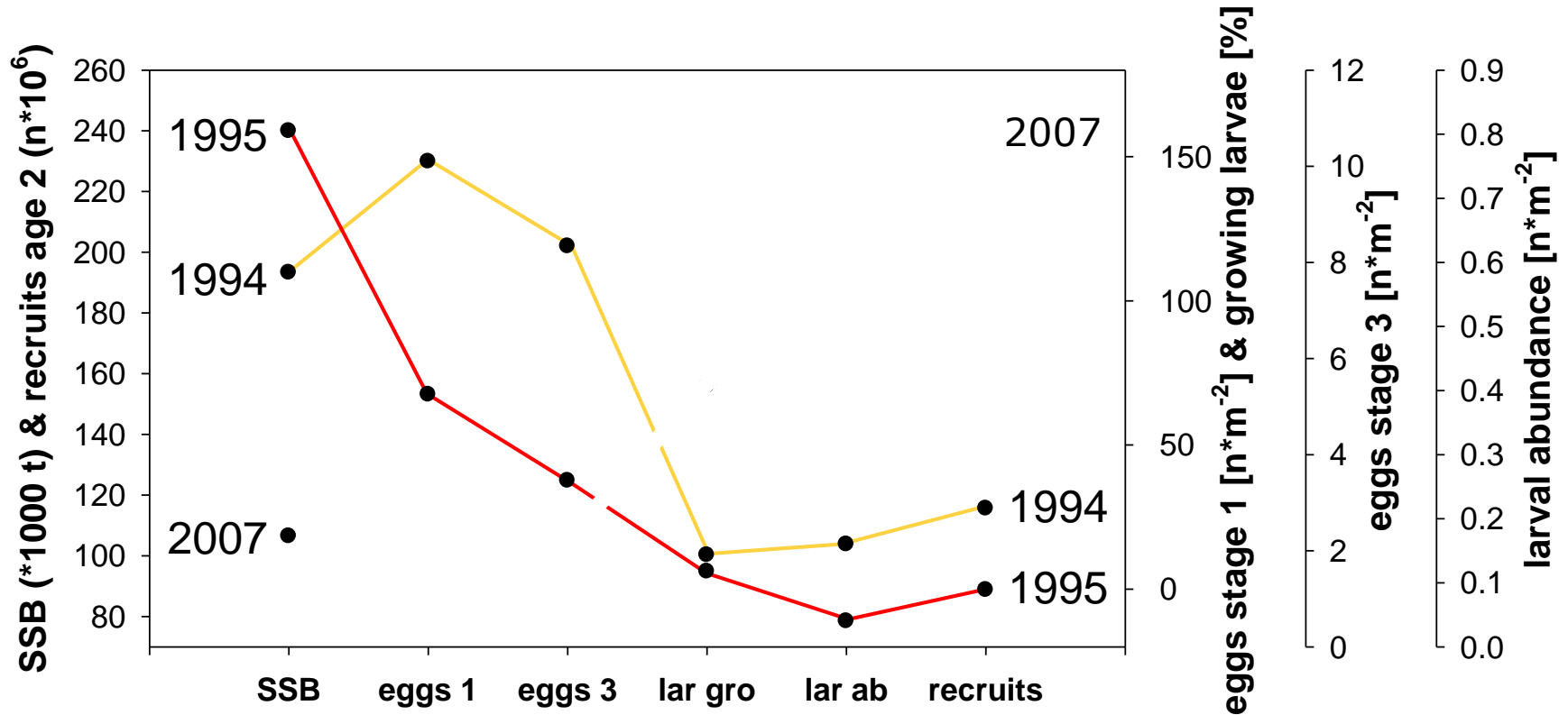
What is different now ?

First order controlling factors

- 1) Stagnation, i.e. loss of 2 spawning areas in the 1980's, caused by lack of major Baltic inflows and eutrophication, i.e. reduced salinity and oxygen
 - No change in the east !
 - Stock uses successfully Arkona Basin as spawning area
 - Summer inflows improve spawning conditions in Bornholm Basin
- 2) Prey availability for first feeding larvae, i.e. decline in marine copepod during the 1990's, caused by reduced salinity and predation by sprat
 - Have larval feeding conditions and survival improved ?

Larval survival

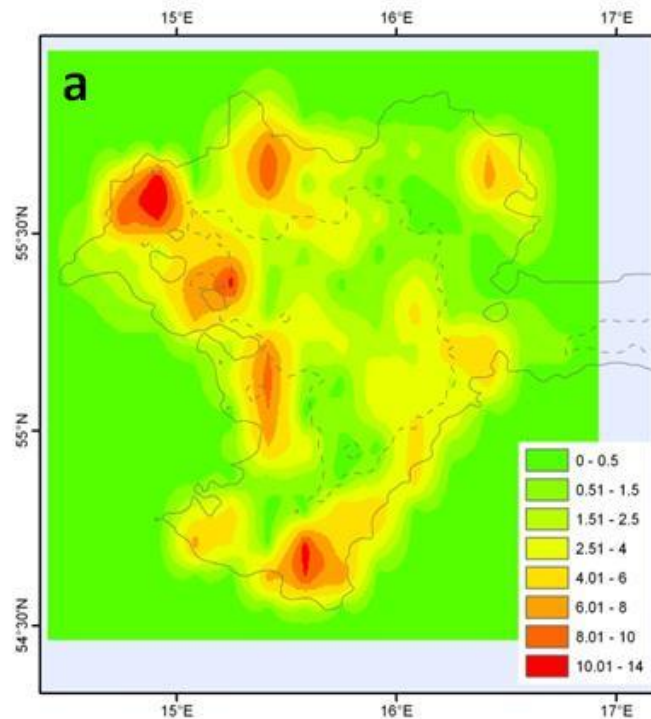
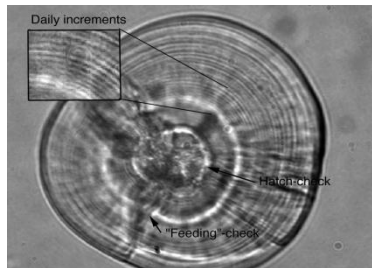
Contrasting cohort survival in mid 1990's and in recent years indicates differences in survival and processes acting



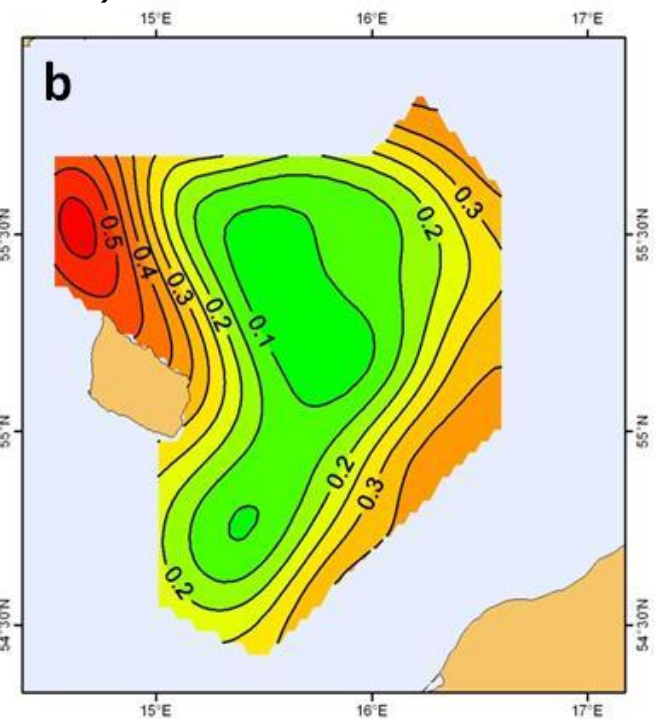
Relatively high larval growth rate and survival during the larval stage !

Larval survival

Back-calculated hatch positions of pelagic juvenile survivors based on otolith age readings and backtracking by drift model (Huwer et al. 2011b)



Modelled survival probability in a situation with low abundance of *Pseudocalanus* (Hinrichsen et al. 2002)



Summer inflows keeping eggs high in the water column, thus not only in the central Basin

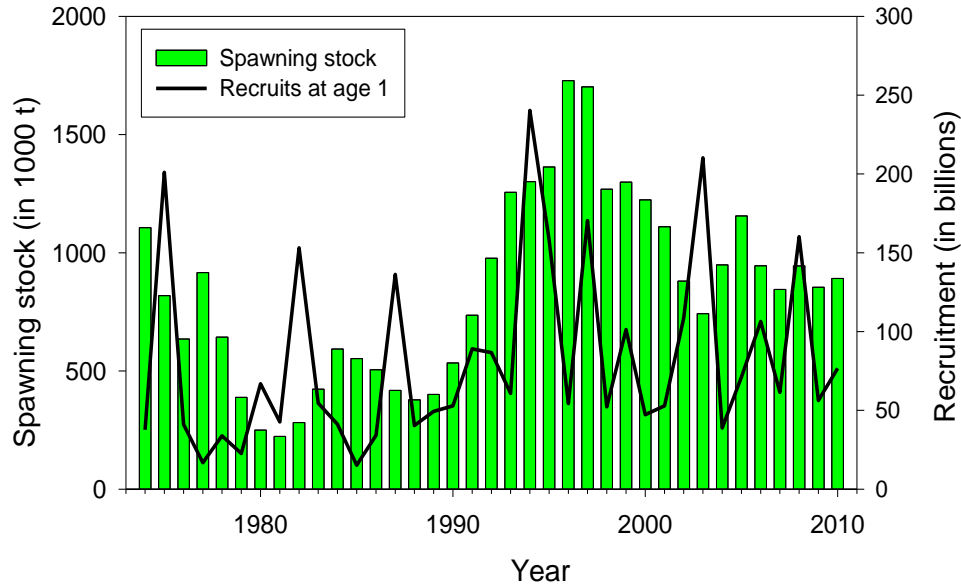
What is different now ?

First order controlling factors

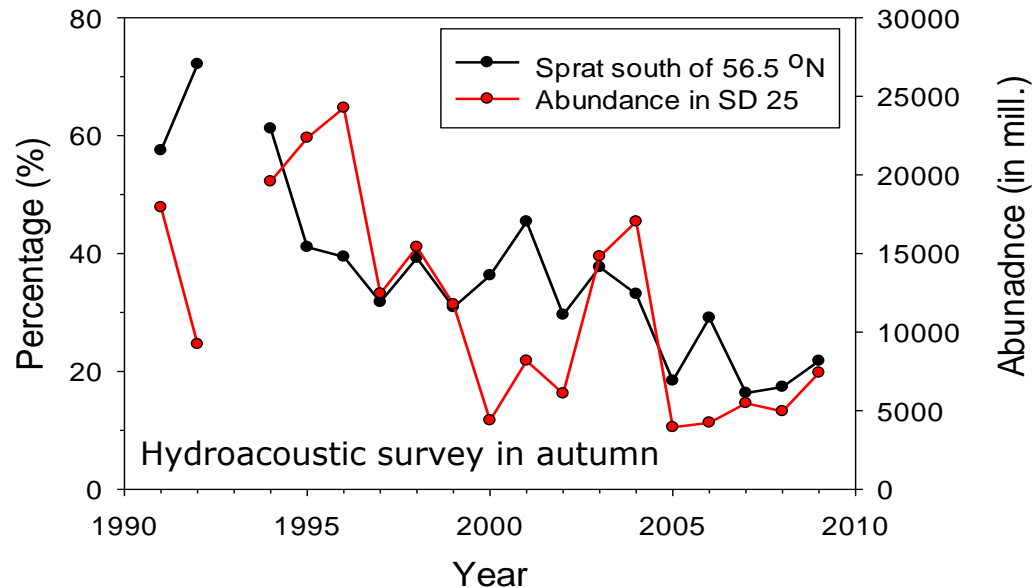
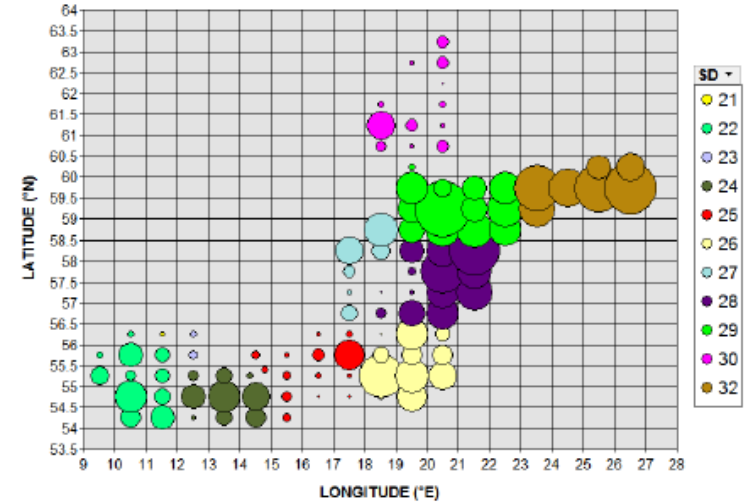
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- 2) Prey availability for first feeding larvae, i.e. decline in marine copepod during the 1990's, caused by reduced salinity and predation by sprat
 - High larval growth is possible during summer when larvae hatch on Basin slopes, sustained by summer inflows
 - What about sprat ?

What about sprat ?

Spawning stock size and recruitment



Abundance from hydroacoustic survey in autumn 2010



moved north-wards in response to milder winters

and declined in southern areas due to harder fishing

What is different now ?

First order controlling factors

- 1) Stagnation, i.e. loss of 2 spawning areas in the 1980's, caused by lack of major Baltic inflows and eutrophication, i.e. reduced salinity and oxygen
 - No change in the east !
 - Stock uses successfully Arkona Basin as spawning area
 - Summer inflows improve spawning conditions in Bornholm Basin
- 2) Prey availability for first feeding larvae, i.e. decline in marine copepod during the 1990's, caused by reduced salinity and predation by sprat
 - High larval growth is possible during summer when larvae hatch on Basin slopes, sustained by summer inflows
 - Overall stock size of sprat still high, but decline in southerly areas, with consequence of decreasing predation on cod larval prey species

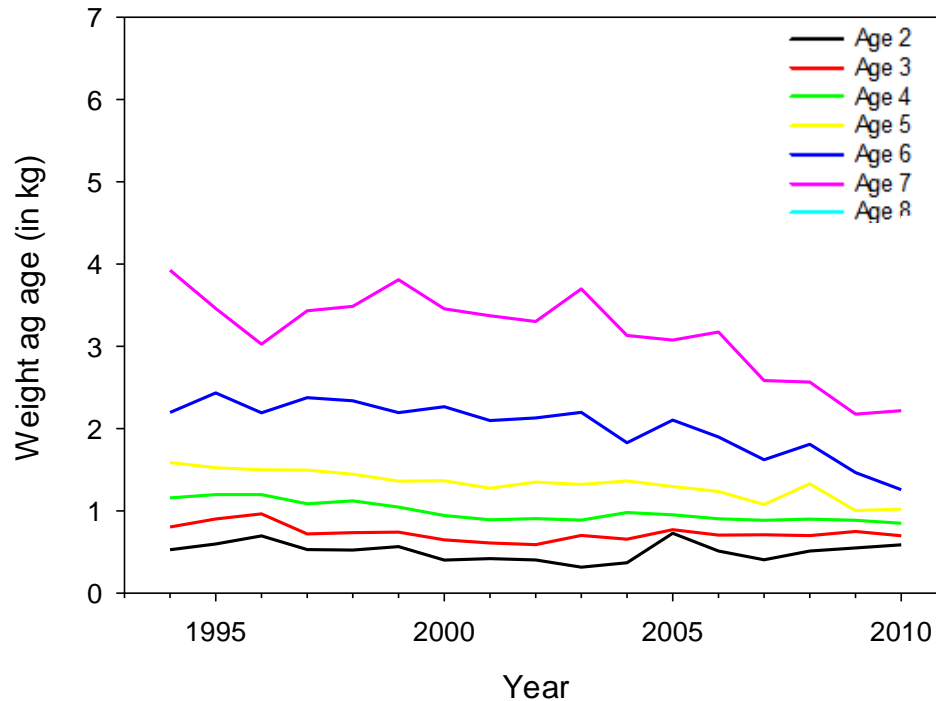
Second order regulating factors

- 3) Egg predation by herring and sprat especially in 1980's, depending on salinity/oxygen and timing of spawning defining vertical and horizontal overlap between predator and prey, respectively
 - Egg predation by sprat declined
- 4) Prey availability affects egg production by adult stock, depending on sprat stock dynamics (has increased in 1990's)
 - Does condition and growth change ?

Effects of prey availability ?

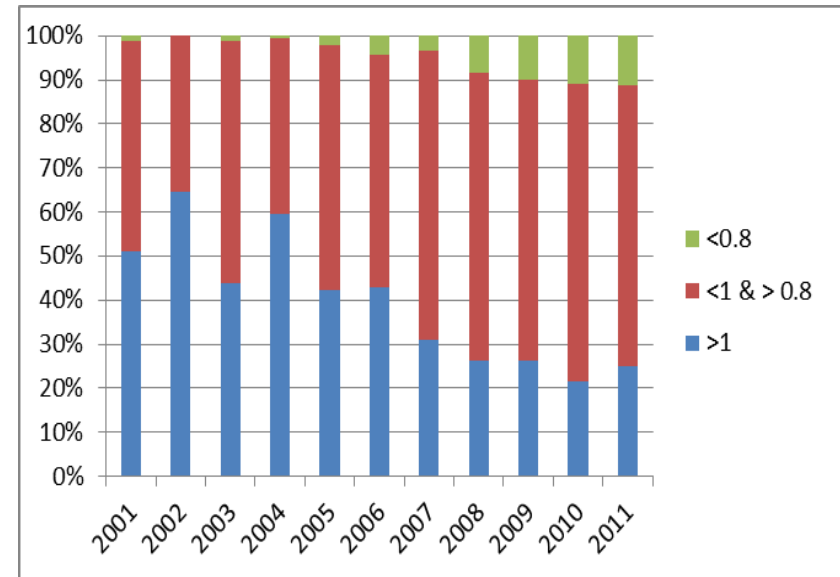
Has reduced prey availability an effect on cod growth and condition ?

Weight at age in catch



Weight at age of cod declined in older ages from early 2000's

Condition factor (1st quarter Bornholm)



Proportion of cod in poor condition increased as well

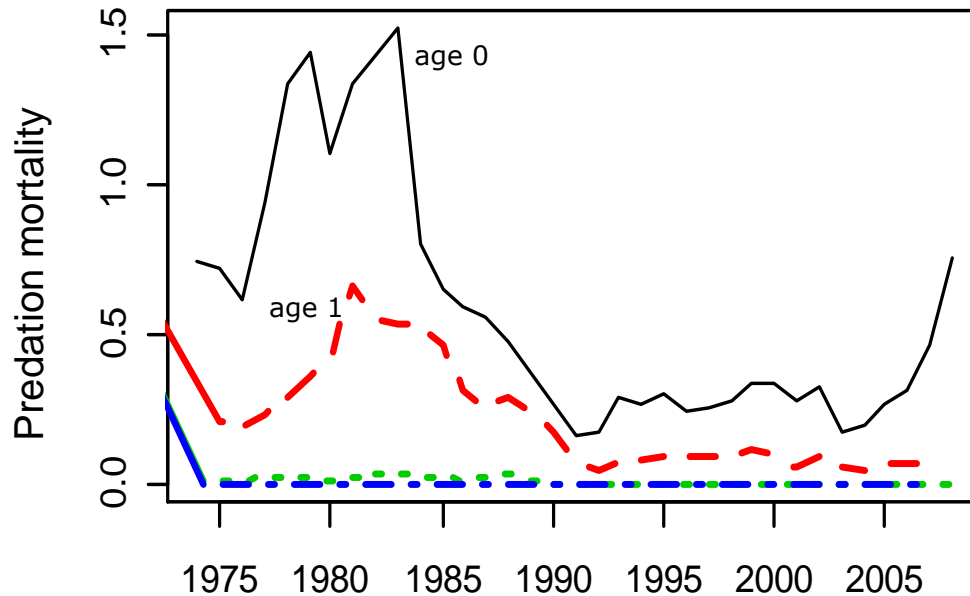
What is different now ?

Second order regulating factors

- 3) Egg predation by herring and sprat especially in 1980's, depending on salinity/oxygen and timing of spawning defining vertical and horizontal overlap between predator and prey, respectively
 - Egg predation by sprat declined
- 4) Prey availability affects egg production by adult stock, depending on sprat stock dynamics (has increased in 1990's)
 - Needs follow-up, so far not conclusive
- 5) Cod cannibalism, depending on transport of juveniles, temperature and oxygen defining horizontal overlap to adults (has decreased through 1980's), cod stock structure (older fish are more effective predators) as well as abundance of alternative prey (has increased during 1990's)
 - With increased proportion of older fish in the stock and reduced sprat as prey, does cannibalism increase ?

Effect of cannibalism

Predation mortality of different ages from multispecies assessment model



Removal during the 1970-80's:
60% of the 0-group
30% of the 1-group

during the 1990's-mid 2000's:
23% of the 0-group
9 % of the 1-group

since 2006:
increasing due to higher
proportion of older fish
and increased overlap between
predator and prey

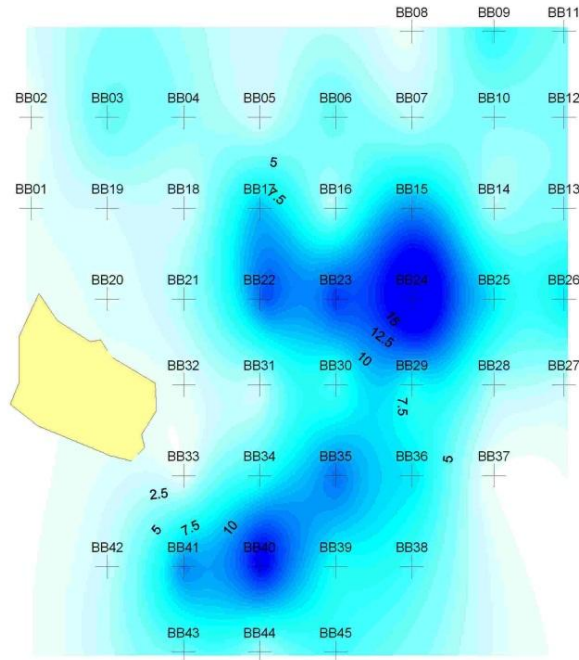
Summary

1. Eastern Baltic: pronounced decline in fishing mortality (F) and increasing stock
2. Western Baltic: tendency of declining F, but no increase in stock size (pattern may emerge from eastern fish caught in Arkona Basin)
3. Reduction of F in eastern stock is driven by:
 - catch reductions,
 - increased recruitment
4. Increase in stock is to a large extent driven by recruitment
5. Reproductive success is enabled by:
 - utilising the Arkona Basin for spawning
 - summer inflows in the Bornholm Basin enhancing egg survival
 - improved nutritional condition/growth of larvae, e.g. low abundance of marine copepod compensated by utilising summer production of other copepods, enabled by successful hatching on basin slopes
 - declined cod egg predation by sprat due to large-scale changes in distribution of predator, with herring stock still on relatively low level
 - declined predation by sprat on copepods serving as food for cod larvae

Processes above need validation !

Things to come

Cod larvae / m² (preliminary abundance August 2011)



Offspring production continues to be high

Highest larval abundance in 25 years !

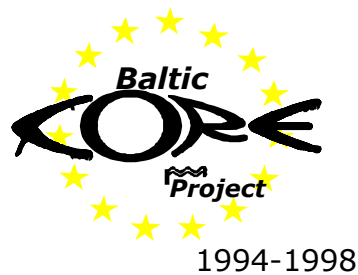
Survival success needs to be seen !

However, density dependent compensatory processes will slow down population growth:

- decline in sprat in SD25 has apparently a negative effect on cod growth and condition with impact on maturation and egg production likely also survival of offspring,
- cod cannibalism is expected to increase.

Thank's for listening !

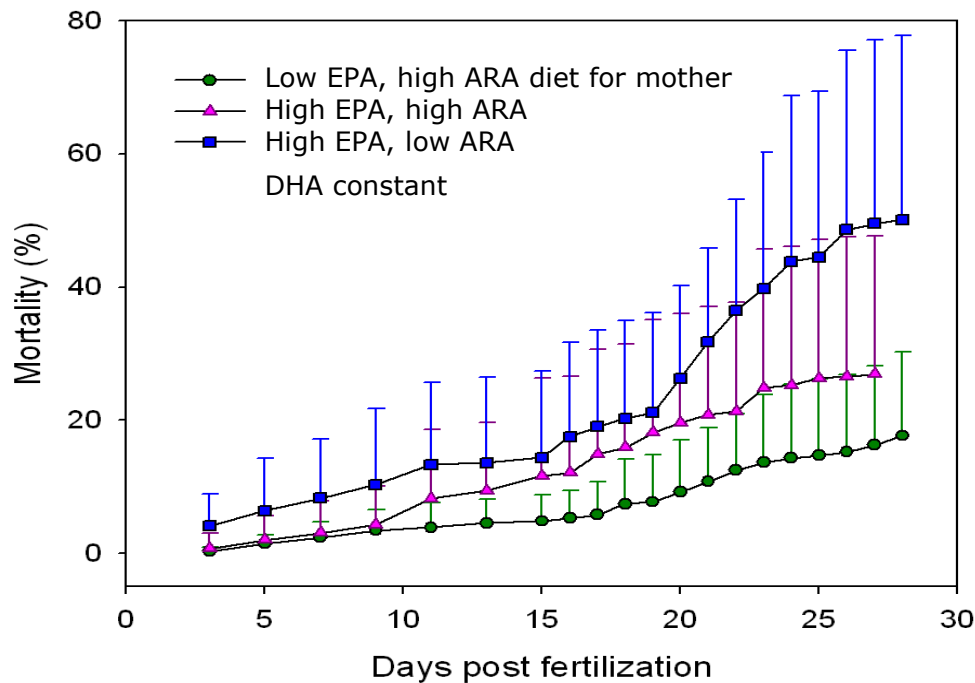
Financial support from EU, German Ministry of Science and Technology,
Danish Strategic Research Council and Femern Bælt A/S



Effects of prey quality ?

In general Eastern Baltic cod have a high level of liver lipids, however, low level of the n-6 essential fatty acid Arachidonic acid (ARA) could be a limiting factor.

Preliminary experiment conducted with Atlantic cod



ARA supply affects directly larval development success !

ARA limitation may be related to phyto- and zooplankton composition (traditional assumption)

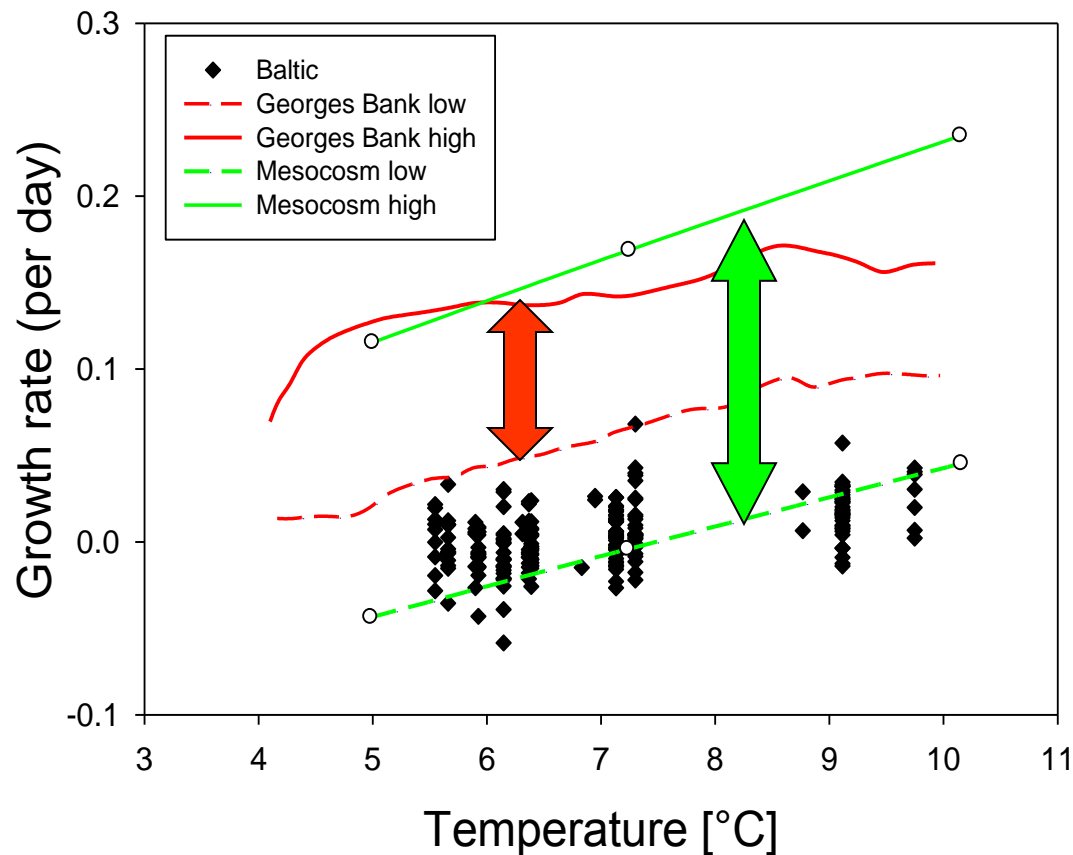
... or availability of benthic invertebrates, which are rich in ARA ?



Impact of combined reduction in growth and limitation of ARA on recruitment uncertain !

Larval survival and prey availability

Growth performance of Eastern Baltic cod larvae (2007) in comparison to cod from other areas

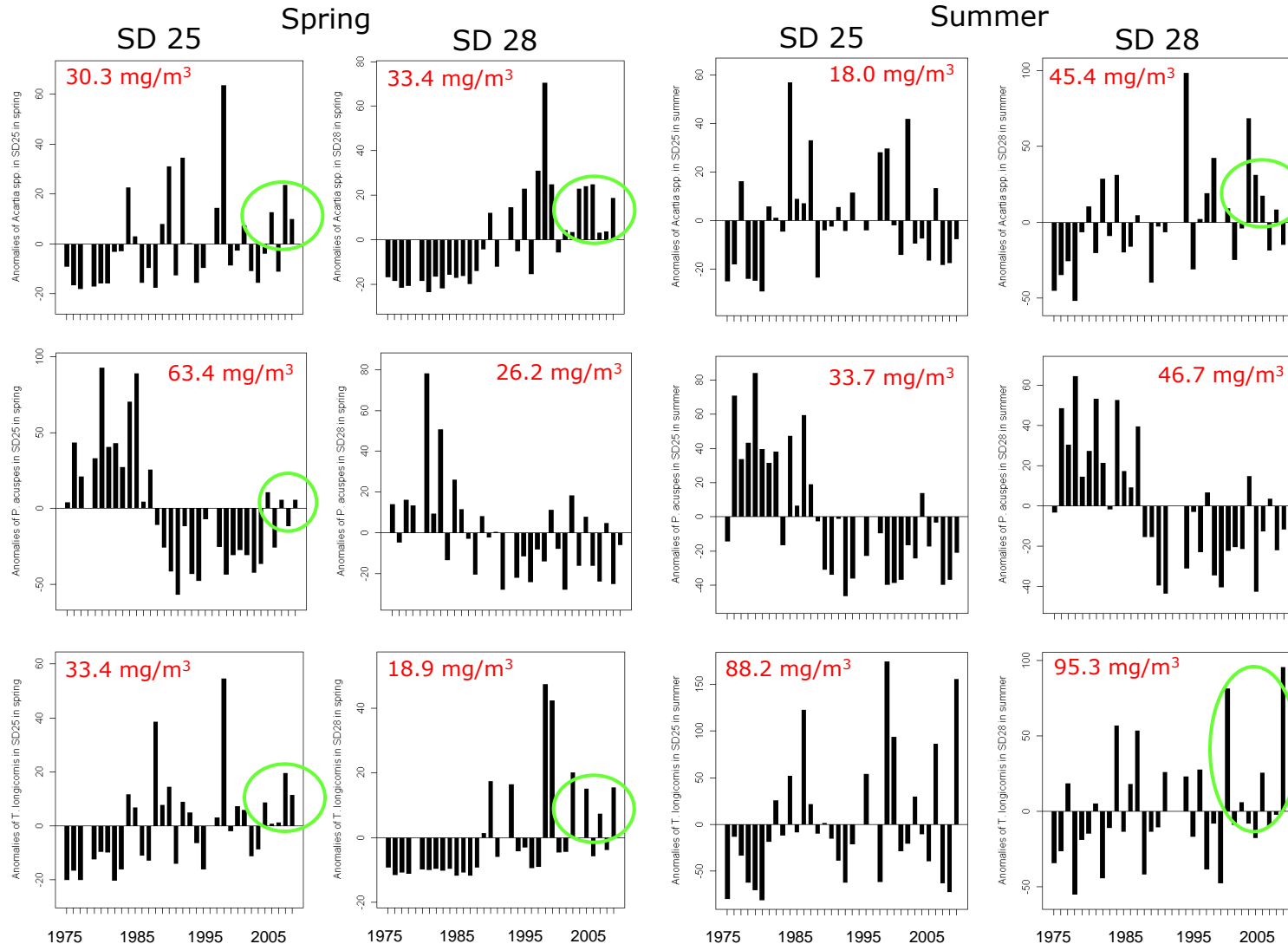


At lower end of
larvae from mesocosm

Below larvae from
Georges Bank

Zooplankton dynamics in SD 25 and SD 28

Biomass anomalies of zooplankton species 1975-2008



Acartia spp.

+ in spring
in summer only
in SD 28

P. acuspes

slight
normalisation
in SD 25

T. longicornis

+ in spring
in summer less
clear, but high
biomass

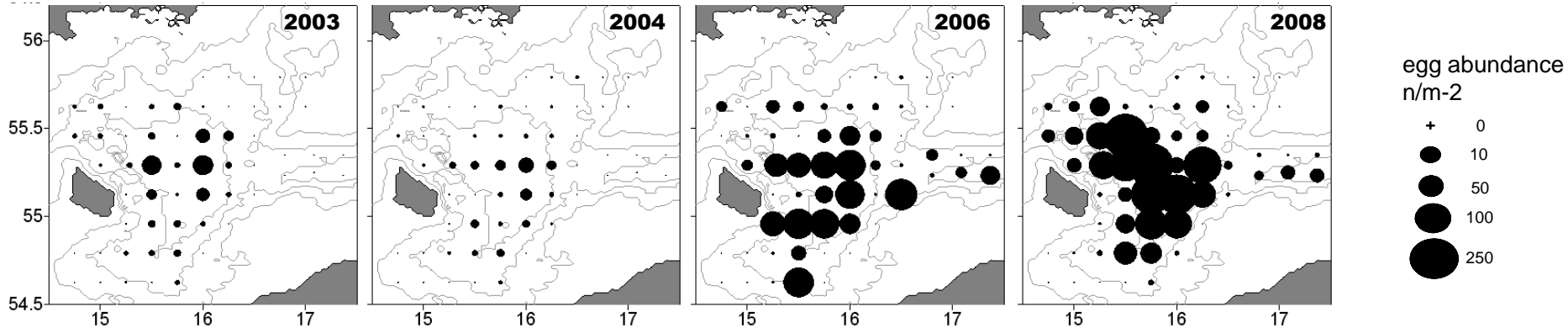
Biomass increased in spring; has spawning time shifted back ?

ICES (2010)

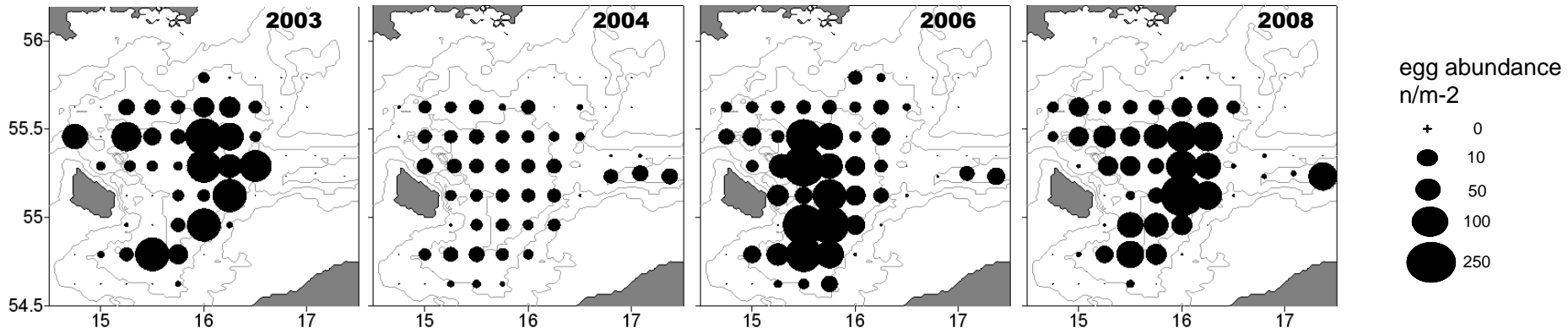
Spawning time of cod

Cod egg abundance in May/June and July/August 2003-2008

May/June



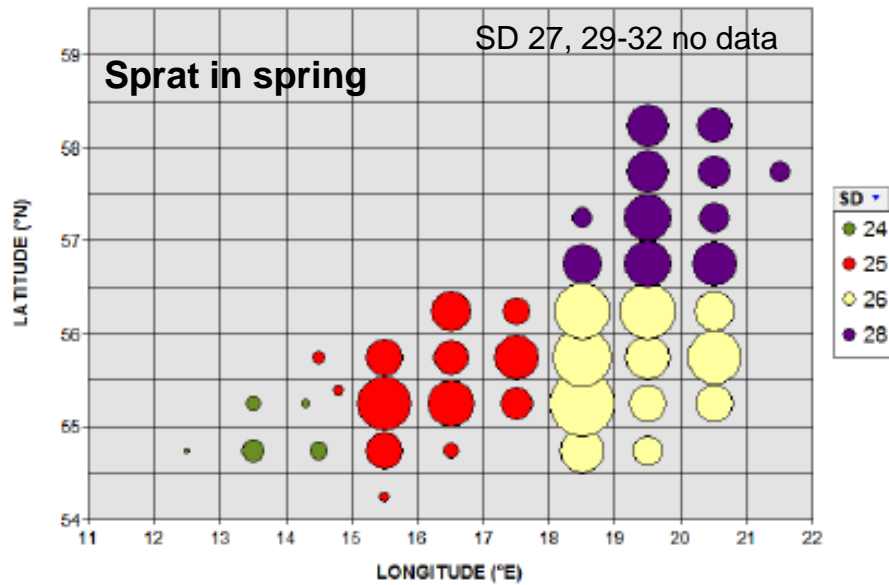
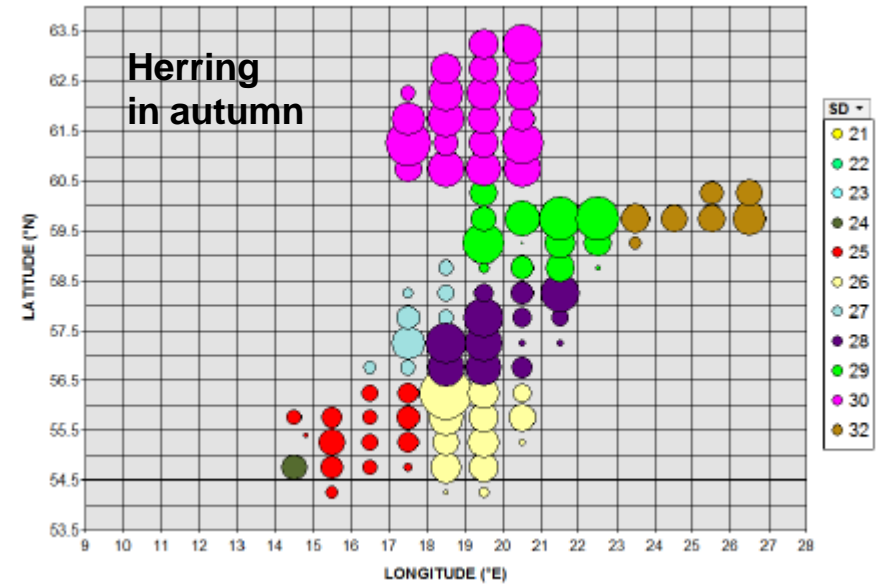
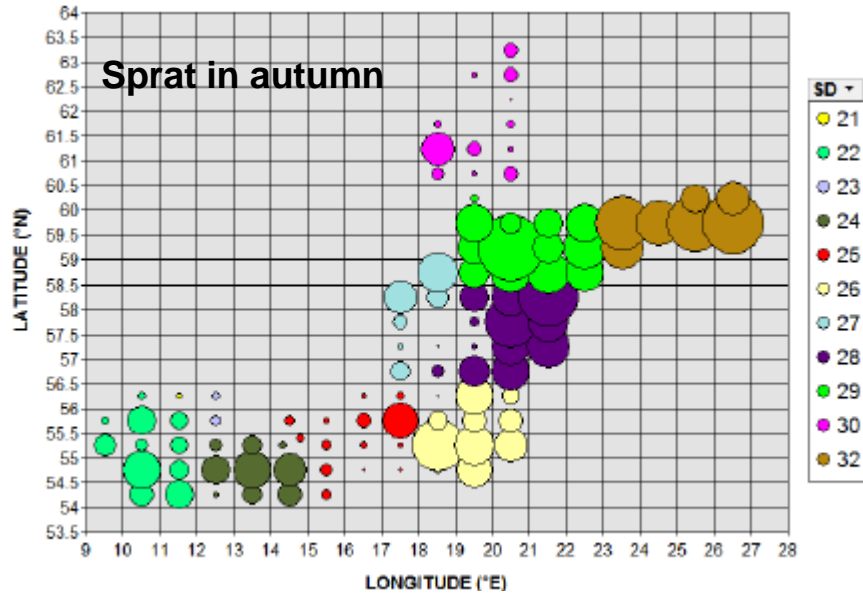
July/August



Spawning time has not shifted back, but extended into spring, being an advantage

Clupeid distribution in the Baltic

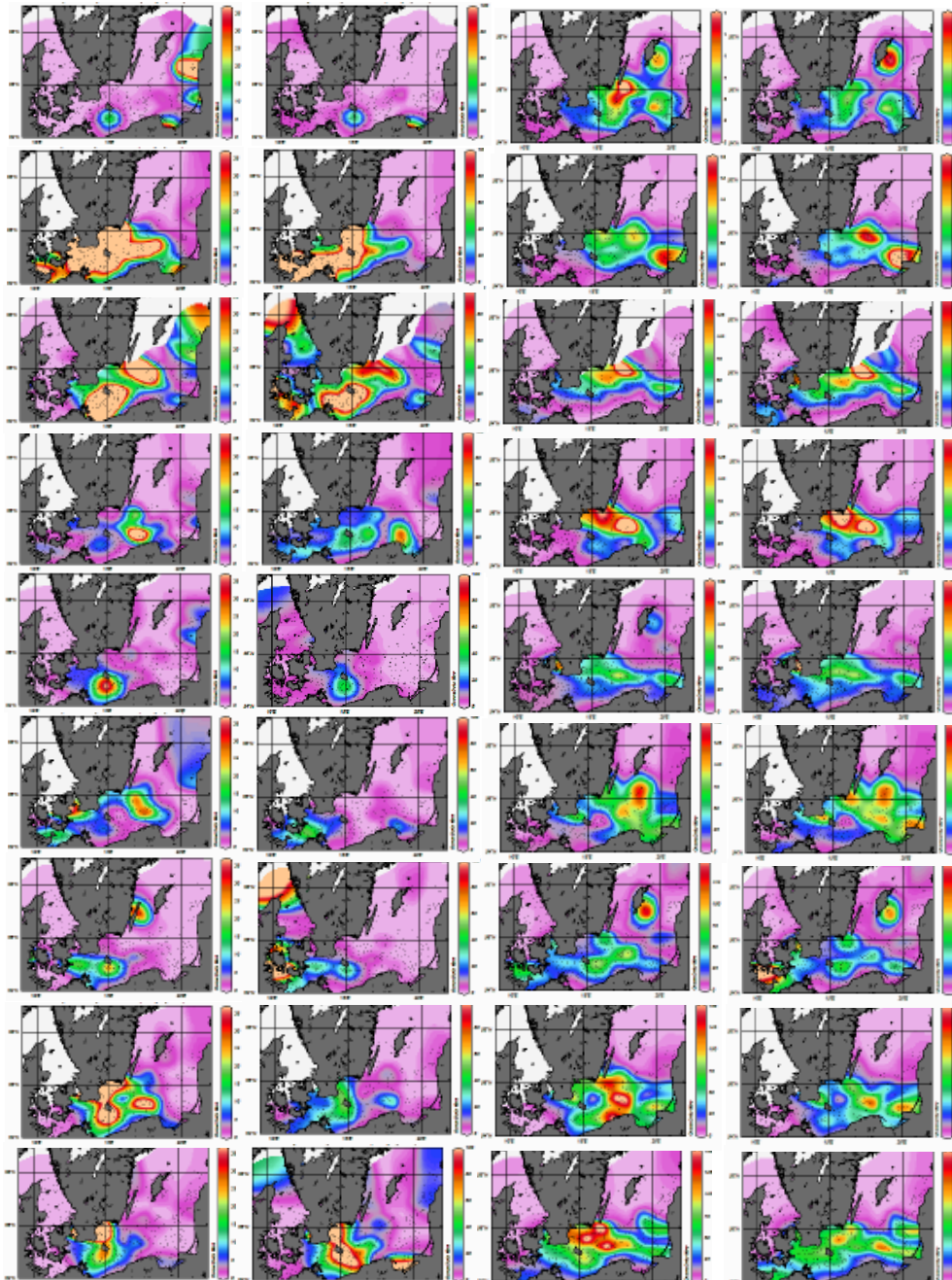
Abundance from hydroacoustic surveys in 2010



Bornholm Basin (SD25): low abundance of sprat and herring in autumn, in spring sprat abundance somewhat higher

Overlap of juvenile and adult cod

Oeberst 2008)



1. quarter 2003
year-class 2002: low
south of Bornholm, **adults further east**

4. quarter 2003
year class 2003: high
entire western Baltic, **some overlap east of BB**

1. quarter 2004
year class 2003 around BB & south/east Øland
overlap to adults in latter area

4. quarter 2004
year class 2004: low-middel
Around BB & along polish coast, **overlap limited**

1. quarter 2005
year class 2004 south of BB, **low overlap**

4. quarter 2005
year class 2005: middel
Most areas of western Baltic, **overlap east of BB**

1. quarter 2006
year class 2005 in western Baltic & south of BB
only in latter area some overlap

4. quarter 2006
year class 2006: middel-high
BB, Hanø Bight & Polish coast, **overlap in latter**

1. quarter 2007
BB, Hanø Bight & Gdansk Bay, **considerable overlap**, except in latter area